SANDIA REPORT

SAND2006-xxxx
Unlimited Release
Printed December 2006

Geologic Technical Assessment of the Bruinsburg Salt Dome, Mississippi, for Potential Expansion of the U.S. Strategic Petroleum Reserve

Christopher A. Rautman, Karl M. Looff, Anna Snider Lord, and John B. Duffield

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of
Energy under Contract DE-AC04-94AL85000.
Approved for public release; distribution is unlimited.

Sandia National Laboratories

The original version of this
draft Sandia Report is
"OFFICIAL USE ONLY",
because of the presentation of.
proprietary information

The proprietary information,
consisting of two illustrations,
as been removed from this copy.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:(865)576-8401
Facsimile:(865)576-5728
E-Mail:reports@adonis.osti.gov
Online ordering: http://www.doe.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone:(800)553-6847
Facsimile:(703)605-6900
E-Mail:orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

Geologic Technical Assessment of the Bruinsburg Salt Dome, Mississippi, for Potential Expansion of the U.S. Strategic Petroleum Reserve

Christopher A. Rautman
Geotechnology and Engineering Department
Sandia National Laboratories
Albuquerque, New Mexico 87185-0706

Karl M. Looff
Geologic Consultant
P.O. Box 546
Lovelady, Texas 75851

Anna C. Snider Lord
Geotechnology and Engineering Department
Sandia National Laboratories
Albuquerque, New Mexico 87185-0706

John B. Duffield
Umbrella Consulting
603 Cranfield Court
Katy, Texas 77450

Abstract

The Bruinsburg salt dome, located in extreme western Mississippi, is a small, shallow-piercement salt stock, which has been proposed as a potential site for expansion caverns for the United States Strategic Petroleum Reserve. This dome is particularly small in size: only about 120 acres, or less than 0.2 square miles in area, at a depth of 2000 ft. The areal extent of salt present within the depth interval normally considered for Strategic petroleum Reserve caverns, approximately 2500 ft to 4500 ft, appears adequate for a *maximum* of seven (7) 10-million-barrel storage caverns.

The geometric shape of the salt dome is structurally complex, and it is considered highly anomalous compared with other shallow, onshore Gulf Coast salt domes. A major portion of the deeper (> ~4000 ft) salt stock appears to have been faulted, or otherwise removed from the shallower part of the dome along most, if not all of the southern half of the dome. The apparent replacement of a large part of the shallow salt by faulted blocks of sediment severely restricts the area/volume of salt available for construction of underground storage caverns. This interpretation is based upon geologic studies using a very limited number of drill hole control points and four (4) two-dimensional seismic lines that cross the dome area, including two new profiles that were acquired as part of this investigation.

Executive Summary

The Bruinsburg salt dome is a small, shallow-piercement salt stock, less than approximately one-quarter square mile in area near the top of salt. the dome is located mostly within the flood plain of the lower Mississippi River, in extreme western Mississippi, approximately 70 miles west-southwest of the state capitol of Jackson.

Geologic description of the Bruinsburg dome is complicated by the small total number of oil & gas wells, and other borings, that have been drilled in the general vicinity. A severe problem, affecting all of the geologic characterization effort, is that land-survey boundaries in this area are spatially uncertain, and the positions of section lines vary depending upon the source of the information. The locations of wells and drill holes, most of which have been surveyed from section corners and other elements of the land survey, are also highly uncertain, and collar locations vary by source reference. Discrepancies are typically on the order of 500 ft, but may exceed this value. Additionally, well control is clustered and spatially biased, providing virtually no subsurface control over much of the dome area.

Two 1970s-vintage two-dimensional seismic profiles have been licensed and reprocessed for this study using current modeling algorithms. Two new 2-D seismic lines have been acquired and processed, as part of this investigation, and the results of all four seismic lines have been incorporated into the geologic description. Whereas the two 1970s seismic lines appear to have been affected by the general spatial uncertainty and inconsistencies associated with the land-survey grid, the new-generation shotpoints were surveyed using Global Positioning Satellite (GPS) technology, and these positions presumably are highly accurate. GPS survey locations are completely independent of the land-survey issues.

The geometry of the salt stock, as revealed principally by the two-dimensional seismic profiling, is complex and highly atypical of shallow Gulf Coast onshore salt domes. The boundary between salt and the adjoining sediments has the form of a concave-upward listric (?) fault (?), apparently around the entire southern periphery of the dome. Tilted and faulted sedimentary reflectors above this surface overlie a much larger, more circular mass of salt.to a depth of 3500–4000 ft. Part of this more typical portion of the deeper salt stock exhibits up to 800 ft of structural overhang between 4000 and 7000 ft. The anomalous structural boundary severely limits the area and volume of salt available for cavern development within the usual depth interval of about 2500 to 4500 ft. Sediments overlying the salt and its caprock appear to be complexly faulted, as well.

The shallow portion of the Bruinsburg salt stock may prove suitable for a small, 50- to 70-million-barrel Strategic Petroleum Reserve (SPR) storage facility, consisting of a maximum of seven (7) standard SPR Level-3-design caverns. This non-optimized, conceptual cavern layout considers a 300-ft regulatory standoff distance from the modeled edge of salt. Use of a 500-ft buffer zone, in light of the degree of uncertainty associated with the complex geology, limited data set, an spatial-positioning issues, would allow a maximum of perhaps three to four storage caverns.

The anomalous geology of the souther part of the salt stock is not well understood, and the additional complications of the structure in this area render the Bruinsburg dome a high-risk potential SPR expansion site. Significant additional geologic characterization, including both seismic surveys and drilling, is required if a decision is made to proceed with selection of this site.

CONTENTS

Abstract . . . 3

Executive Summary . . . 4

Figures . . . 5

Tables . . . 7

Plates . . . 7

Introduction . . . 9

Geology of the Bruinsburg Salt Dome . . . 10

Background and Previous Investigations . . . 10

Available Data . . . 11

Well Information . . . 11

Spatial Uncertainty . . . 11

Forest Oil 2-D Seismic Lines . . . 13

Seismic Survey Acquired for this Study . . . 15

Geometry of the Salt Stock . . . 15

Seismic Data and Profile Interpretation . . . 15

Mapping of the Salt Margin . . . 21

Mapping of the Caprock . . . 27

Structural Interpretation . . . 28

Three-Dimensional Modeling . . . 28

Estimates of the Area and Volume of Salt available for Development . . . 35

A Possible SPR Cavern Layout at the Bruinsburg Site . . . 40

Discussion . . . 42

Summary and Conclusions . . . 44

References . . . 45

FIGURES

1. Index map showing the location of the Bruinsburg salt dome in extreme western Mississippi, together with the locations of the four currently active Strategic Petroleum Reserve facilities. . . . 9

2. Map showing locations, and inconsistencies in reported locations, for wells relevant to mapping the Bruinsburg salt dome. . . . 12

3. Simplified map showing locations of the preexisting non-exclusive 2-D seismic surveys in the general vicinity of the Bruinsburg salt dome. . . . 13

4. Small-scale index map showing the locations of the two newly acquired Sandia seismic lines and the two previously existing Forest Oil lines. . . . 14

5. Uninterpreted (top) and interpreted (bottom) images of Sandia seismic line 12, showing geometry of the Bruinsburg salt dome. . . . 16

6. Uninterpreted (top) and interpreted (bottom) images of Sandia seismic line 11, showing geometry of the Bruinsburg salt dome 18

7. Uninterpreted (top) and interpreted (bottom) images of Forest Oil seismic line 2, showing geometry of the Bruinsburg salt dome. 19

8. Uninterpreted image of Forest Oil seismic line 1, showing off-dome geometry of sediments surrounding the Bruinsburg salt dome. 20

9. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 120°, elevation 30°. 22

10. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 225°, elevation 30°. 23

11. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 285°, elevation 30°. 24

12. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 60°, elevation 50°. 25

13. Small-scale map showing depth intercepts for the salt margin of the Bruinsburg salt dome on three seismic profiles. 26

14. Time-to-depth conversion graph for sediments in the vicinity of the Bruinsburg salt dome. 27

15. Small-scale structure-contour map showing the geometry of the top of the Bruinsburg caprock. 29

16. Small-scale structure-contour map showing the top and flanks of the Bruinsburg salt dome, as interpreted from seismic and well data. 30

17. Map view of the three-dimensional geologic model of the caprock of the Bruinsburg salt dome. 31

18. Perspective views of the Bruinsburg caprock model from (a) azimuth 210°, elevation 50°, and (b) azimuth 150°, elevation 50°. 32

19. Perspective views of the Bruinsburg caprock model from (a) azimuth 60°, elevation 50°, and (b) azimuth 345°, elevation 50°. 33

20. Map view of the 3-D model of the Bruinsburg salt dome showing the geometry of the top-of-salt surface. 34

21. Perspective views of the geometry of the Bruinsburg salt dome. 36

22. Perspective views of the geometry of the Bruinsburg salt dome. 37

23. Perspective view of the Bruinsburg salt dome from azimuth 105°, elevation 20°, emphasizing the geometry of the southern flank, interpreted as a possible listric fault. 38

24. Conceptual illustration of generating area and volume estimates from a 3-D model of a salt dome. 39

25. Increase in salt-stock area as a function of depth, reflecting apparent truncation of the upper part of the Bruinsburg salt dome 40
26. Schematic map of the of the Bruinsburg salt dome showing approximate dimensions of a potential SPR seven-cavern layout. 41
27. Perspective views of the 3-D model of the Bruinsburg salt stock showing effect of standoff buffer zones from the salt margin. 43

TABLES

1. Total Estimated Area and Volume of the Bruinsburg Salt Dome 39
2. Change in Estimated Size of the Bruinsburg Salt Dome, Considering Standoff Zones 41
A-1. Locations and Basic Interpreted Data for Exploratory Wells Available for Characterization of the Bruinsburg Salt Dome 49

PLATES

1. Wells Relevant to Top of Salt, Bruinsburg Salt Dome, Mississippi . . . . . . in pocket
2. Seismic Intercepts on Top and Flanks of Salt, Bruinsburg Salt Dome, Mississippi . . . . in pocket
3. Structure Contours on Top of Caprock, Bruinsburg Salt Dome, Mississippi . . . . in pocket
4. Structure Contours on Top of Salt, Bruinsburg Salt Dome, Mississippi . . . . in pocket
5. Potential Shallow Cavern Layout, Bruinsburg Salt Dome, Mississippi . . . . in pocket

This page intentionally left blank.

INTRODUCTION

The Bruinsburg, Mississippi, site is one of several salt domes identified as possible candidates for potential expansion of the United States Strategic Petroleum Reserve. The Strategic Petroleum Reserve (SPR) was created to store an emergency reserve of crude oil in large underground caverns leached into buried salt domes, located along the Gulf Coast of Texas and Louisiana. The SPR currently operates such underground facilities at the four locations indicated in figure 1. The total capacity of the four SPR sites currently is 727 million barrels.

The Energy Policy Act of 2005 (P.L. 109-58) directs the U.S. Department of Energy (DOE) to investigate options for expanding the Reserve by nearly one-half, to its Congressionally authorized capacity of one billion barrels. Although some of this expansion will be accommodated by the construction of additional storage capacity at one or more of the existing SPR sites, the magnitude of the required expansion dictates that at least one new site be developed.

The Energy Policy Act instructs the Secretary of Energy first to consider locating potential expansion sites at salt domes that were studied previously for this purpose during earlier planning for expansion (DOE, 1991a, 1991b). Additionally, the Act states that the Governor of a state, in which one or more of those earlier-considered sites was located, may request the DOE to consider additional sites within that state. Accordingly, the Governor of the State of Mississippi has asked the Secretary of Energy to consider the Bruinsburg salt dome, located in extreme western Mississippi, as a candidate site for SPR expansion (Barbour, 2005). The location of the Bruinsburg salt dome is also indicated on the Gulf Coast index map of figure 1.

Figure 1. Index map showing the location of the Bruinsburg salt dome in extreme western Mississippi, together with the locations of the four currently active Strategic Petroleum Reserve facilities.

This report describes the geology of the Bruinsburg salt dome, as it relates to potential selection of this site for possible SPR expansion. The assessment of the geology is based upon both published and unpublished existing data, as well as upon newly acquired two-dimensional seismic lines that were acquired specifically for Sandia National Laboratories and the DOE.

GEOLOGY OF THE BRUINSBURG SALT DOME

Background and Previous Investigations

The Bruinsburg salt dome is located in Claiborne County, Mississippi, approximately 70 miles west-southwest of the state capitol of Jackson and roughly 130 miles nearly due north of Baton Rouge, Louisiana (fig. 1). The dome is located, physiographically, at the edge of the active flood plain of the Mississippi River, in the extreme western portion of the state. The Bruinsburg dome has been described in general terms, as part of a comprehensive tabulation of basic data for a large number of shallow salt domes within the State of Mississippi (Thieling and Moody, 1997).

The Bruinsburg salt dome is similar to most of the shallow salt domes in the Mississippi Salt Basin. These domes are relatively small, generally less than a square mile in lateral extent, and they are generally more or less pure piercement domes. Diapiric rise of this type of salt stock is generally late, with respect to the enclosing sediments, and the salt mass merely pierces through the sediments, with minimal effect on the depositional thicknesses of the various units. The enclosing sedimentary layers may be upturned against the flanks of these domes to a greater or lesser extent.

The Bruinsburg dome was first identified via a gravity survey in 1940, which indicated the existence of a significant gravity low over the site. The actual presence of shallow salt was demonstrated in 1944 by the Freeport Sulphur Company. Freeport drilled five wells over the crest of the dome in search of sulphur deposits. The effort was unsuccessful (Swann, 1989). The Freeport Hammett No. 1 well encountered caprock at a depth of 1629 ft, and was terminated shortly after encountering salt at 2016 ft.

The Sun Oil Company drilled the Hammett No. 1A well, also in 1944, in search of hydrocarbons in sediments overlying the crest of the salt stock. This well was successful, and, along with several other wells, produced gas from the Cockfield Formation (Claiborne Group; Middle Eocene age) at depths of less than 1000 ft. This shallow reservoir was depleted, and the Bruinsburg field was abandoned in 1967 (Swann, 1989).

In addition to the early sulphur and hydrocarbon exploration, the Bruinsburg dome was also investigated for possible commercial salt production. A number of wells were drilled for this purpose during the early 1960s by International Salt Company (later Akzo-Nobel Salt). At least some of the intervals penetrated by this exploratory drilling were cored. At least part of the core from this effort is still preserved (2006) by the Detroit Salt Company at an underground salt mine in Michigan (E.Z. Manos, Detroit Salt Company, personal communication, 2006).

A second round of hydrocarbon exploration, focused apparently on deeper flank sediments surrounding the Bruinsburg salt dome, took place during the 1970s and 1980s. Two 2-D seismic profiles were shot over the Bruinsburg area in 1977 (discussed below). One line crossed the main part of the salt dome, but the other line was offset to the east of the main salt mass. The play appears to have been unsuccessful, and no commercial production resulted.

Available Data

The data available for this characterization report for the Bruinsburg salt dome consist of well information, including both geophysical well logs and scout-ticket entries, previous tabulations of formation tops (principally of caprock and salt), and seismic data. Two existing 2-D seismic profiles were licensed for this project, and two new 2-D profiles were shot across the dome for Sandia National Laboratories.

Well Information

A prime, although somewhat generalized, source of data describing the Bruinsburg salt dome is the compendium of shallow salt domes published by the Mississippi Department of Environmental Quality (Thieling and Moody, 1997). In addition to the information contained in this compendium volume, a database of oil industry exploration wells drilled within approximately one to two miles of the known outline of the Bruinsburg dome was purchased from a well-known commercial vendor of well-location data to the oil industry (http://www.tobin.com/). Location data for additional wells were obtained from the interactive website maintained by the State of Mississippi Oil & Gas Commission (http://library.geology.deq.state.ms.us/). Land survey information was obtained from commercial vendors, the U.S. Geological Survey, and other sources, principally Thieling and Moody (1997).

Geophysical well logs, oil-industry scout tickets and completion cards were obtained from log libraries and commercial oil-industry sources. These latter sources of information were used to generate a list of depths (actually subsea elevations) associated with the top of the salt stock and the top of the caprock overlying the salt. Well identifications, locations (coordinates), and the type of data available for each well are tabulated in table A-1, in the appendix of this report.

Plate 1, accompanying this report, shows the wells that are available to provide meaningful control on the geometry of the Bruinsburg salt dome. Figure 2 presents a much-reduced-scale version of the plate.

Spatial Uncertainty

Plate 1 (fig. 2) also illustrates one of the major difficulties at the Bruinsburg site: the spatial positions of features, including historical wells, land-survey boundaries, and others, are uncertain. The location of the same identified feature, obtained from different sources, will plot in different positions depending upon the specific source reference.

The well-location maps of plate 1 and figure 2 show lines connecting locations for a number of the available wells that are derived from different sources. The difference in spatial position (well 20021, table A-1) may approach 2000 ft, for one particularly egregious example. However, differences on the order of 500 ft are quite common.

In addition to the spatial uncertainty involved in the locations of well-based control points for the top of caprock and top of salt, the positions of land-survey boundaries are uncertain as well. These maps (plate 1, fig. 2) also indicate the section lines, as digitized from three different sources. These sources include the 7-½ degree topographic map series (scale 1:24,000) published by the United States Geological Survey, land maps commonly in use by the petroleum industry, and the seismic shotpoint index map acquired with the preexisting 2-D seismic survey, described later in this document. Maps from the county assessor's office were also examined, but these property boundaries are not shown on figure 2 or plate 1. Note that to the extent that the locations of the various wells were surveyed (or

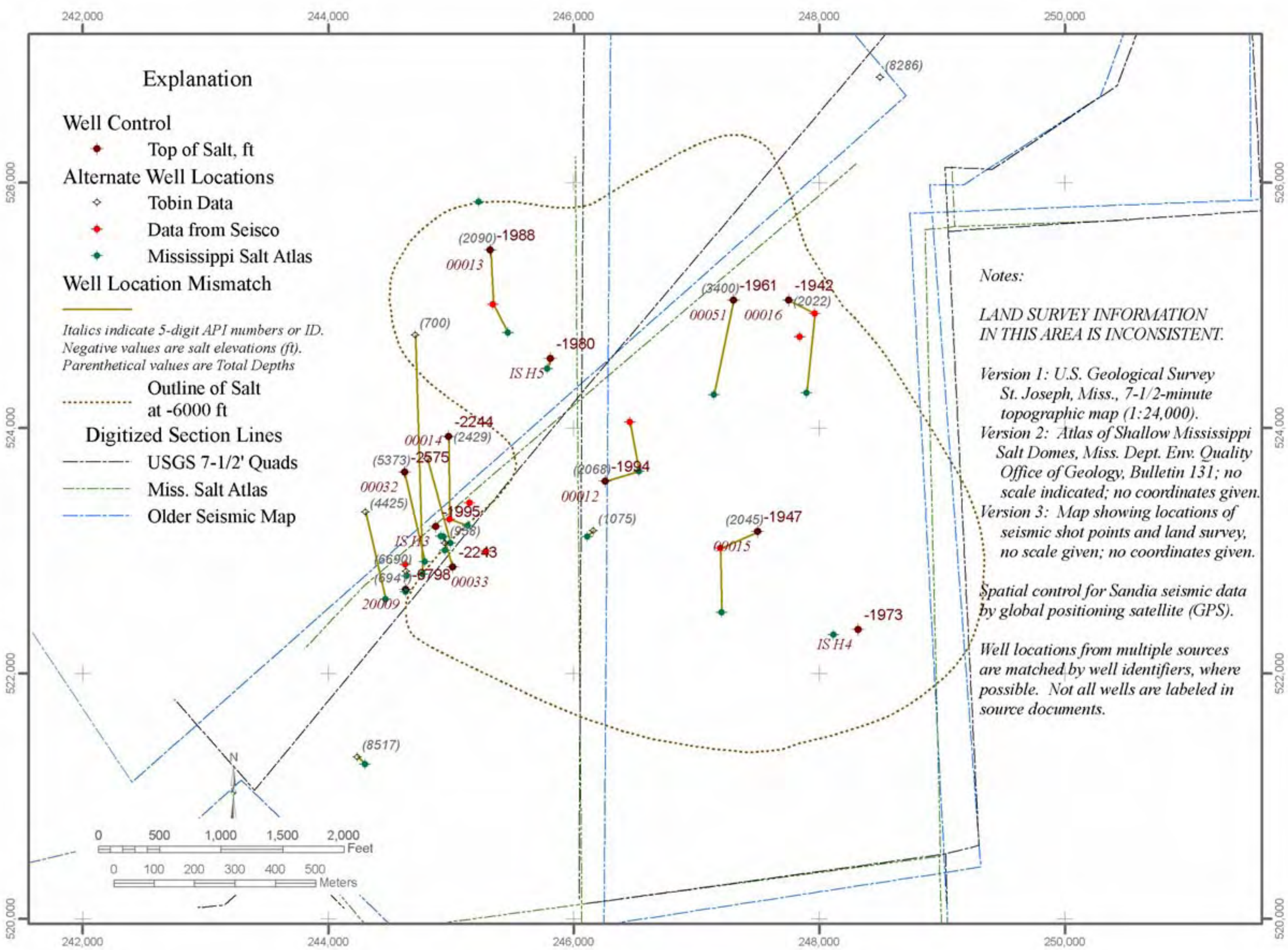


Figure 2. Map showing locations, and inconsistencies in reported locations, for wells relevant to mapping the Bruinsburg salt dome.

plotted) from mislocated or discrepant section corners, errors in the well locations are inevitable.

As will be described below, the shotpoints for the Sandia-contracted 2-D seismic lines were surveyed using Global Positioning Satellite technology; this surveying technique is wholly independent of the land-survey issues. It was not possible to reoccupy either the shotpoints from the earlier seismic survey, or the various section corners, using the GPS system.

Forest Oil 2-D Seismic Lines

Early in this investigation, a search for existing seismic data in the vicinity of the Bruinsburg salt dome was conducted by a broker of such information for the oil industry. A small number of older 2-D seismic lines were identified, as portrayed in figure 3. No existing three-dimensional seismic surveys could be identified.

We examined the quality-control information (recording and processing parameters) for each of the available lines that was thought, a priori, to be of potential value for characterizing the Bruinsburg dome. Most of these lines were eliminated from further consideration by this examination, as too old or shot for purposes incompatible with imaging of the shallow portions of a salt stock.

However, two of the 2-D seismic lines were licensed by Sandia National Laboratories on behalf of the U.S. Department of Energy. The more detailed location of these survey lines is indicated on figure 4. The two lines were shot in the field during 1977, and they are referred to here as the “Forest Oil” seismic lines. Forest Oil is reported to have drilled two dry holes to test prospects generated using

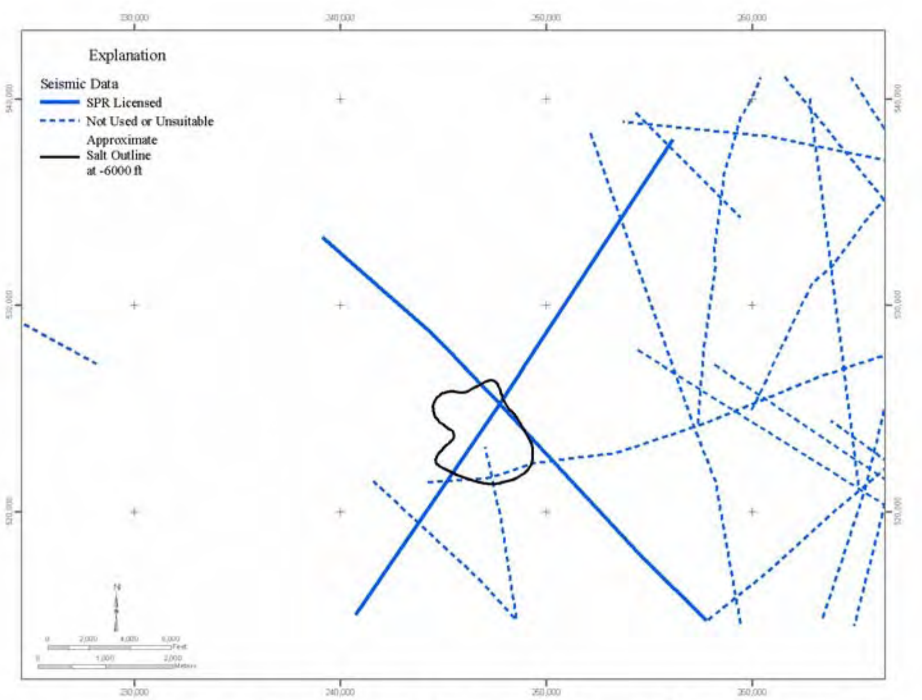


Figure 3. Simplified map showing locations of the preexisting non-exclusive 2-D seismic surveys in the general vicinity of the Bruinsburg salt dome. See discussion in text regarding spatial uncertainty.

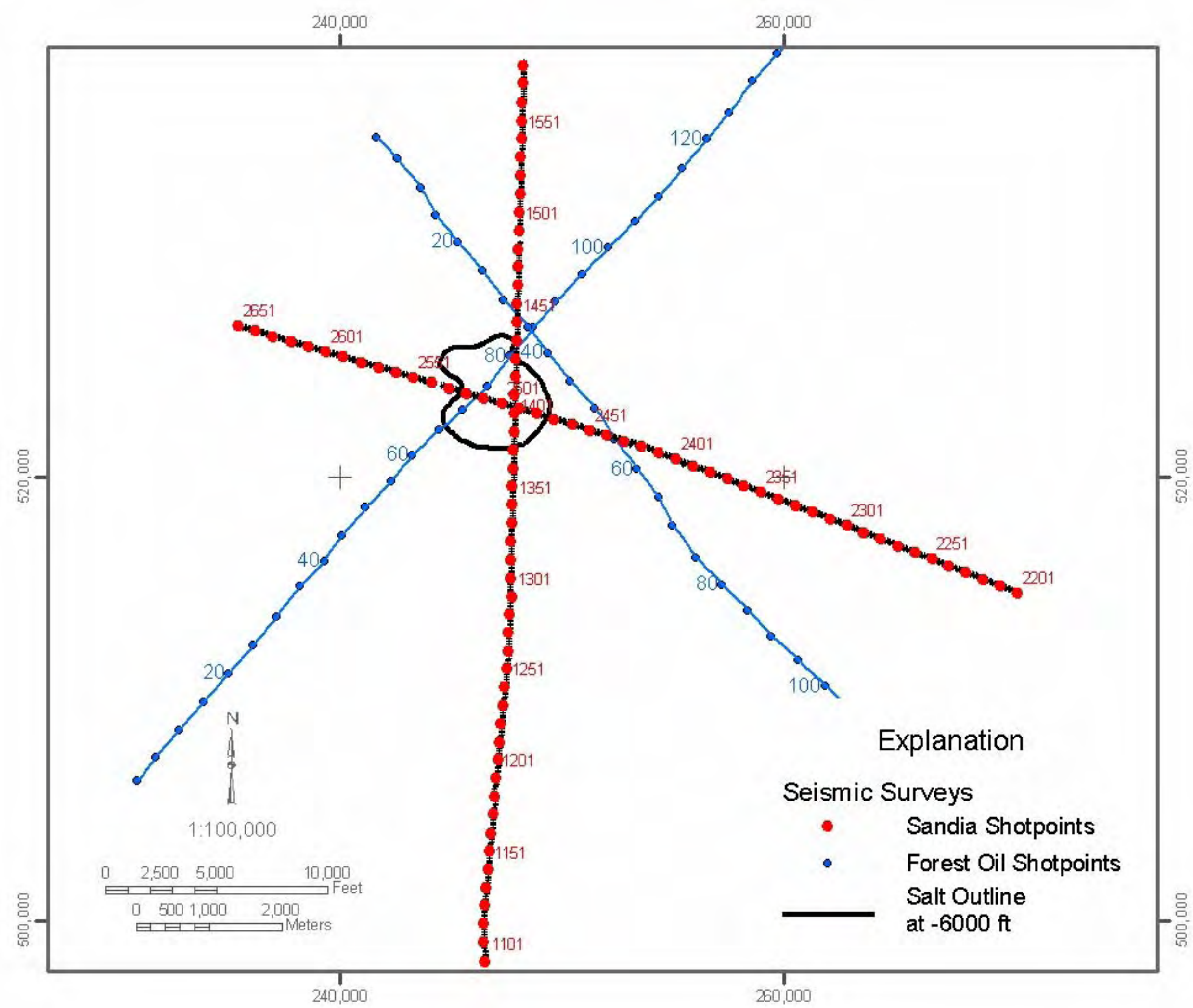


Figure 4. Small-scale index map showing the locations of the two newly acquired Sandia seismic lines and the two previously existing Forest Oil lines.

these seismic lines (Theiling and Moody, 1997).

At some time following Forest Oil's abandonment of the Bruinsburg prospect, rights to the seismic data were transferred to Seisco, Inc., a small broker of seismic data, located in New Orleans, La. (http://www.seiscoinc.com). The lines are licensed from Seisco. As such, the geophysical data, and all "derivative works" produced using that data are proprietary information and protected as for "Official Use Only", under Department of Energy requirements. *Further dissemination of the Forest Oil seismic profiles contained in this report must respect this restriction.* [1]

The Forest Oil data were reprocessed using current technology and the results have been incorporated into the interpretations presented below. Note that there are two versions of the locations of the two 2-D lines, just as there are multiple versions of the locations for the well control. The lines shown on figure 4 are the version that came with the actual field data.

[1] OUO information has been removed from this version of this report, dated December 4.

Seismic Survey Acquired for this Study

Because only one of the extant 2-D seismic profiles appeared to provide meaningful information regarding geometry of the Bruinsburg salt dome, Sandia National Laboratories contracted with Weems Geophysical, of Houston Texas, to acquire two additional 2-D seismic profiles in locations specified by Sandia. Figure 4 also shows the locations of the two Sandia lines.

The new seismic profiles were laid out and the data recorded during the period June through October, 2006. Shotpoints for the two Sandia lines were surveyed using Global Positioning Satellite technology. Accordingly, spatial uncertainty in these locations is probably on the order of a few feet (or less). Final seismic data were made available to Sandia for processing and interpretation in mid-October. Processing of both the Sandia data and the Forest Oil lines was consistent in approach.

Geometry of the Salt Stock

Seismic Data and Profile Interpretation

Four 2-D seismic profiles are now available, from which to interpret the subsurface geometry of the Bruinsburg salt dome. Figures 5 through 8 present processed images of these profiles. Each presentation includes a straightforward, uninterpreted image of each line, at the top of each figure, as well as an identical image, showing our interpretation, at the bottom for three of the lines.

On the interpreted portion of each image, the inferred margin of the salt stock is shown as a heavy, dark-green line. The inferred top of caprock is also shown by a shorter, more horizontally oriented and lighter-green line. Interpreted faults are shown in dark blue, and the line type is dashed. Selected “good” sedimentary reflectors are highlighted by lines of varying color. Although there was some attempt to identify potentially corresponding reflectors across the interruption of the dome, there is no particular meaning to the different colors. Note that these profiles are presented in *time*, not depth. Depth conversion for mapping purposes is described later in this report.

As expected, the sedimentary reflectors outside the dome are turned upward toward the salt margin. Truncation of these inclined reflectors is the principal criterion for identifying the actual margin of the stock. Most truncations are relatively sharp, indicating late piercement of the sediments by the salt, and with little apparent influence of the rising salt mass on depositional thicknesses. Some relatively significant unconformities may be identified on the profiles. These are not investigated in detail, because of our principal interest in the geometry of the salt stock, itself.

Reflections from within the salt mass are generally chaotic. Some more coherent sets of reflectors from within what is interpreted to be salt may be multiples of shallower strong reflectors.

Salt overhang is a prominent interpreted feature of the Bruinsburg salt dome. Because of the differential velocities of salt and prototypical Gulf Coast sedimentary materials, processing of sedimentary reflectors beneath salt may be somewhat problematic. Typically, the strength of sedimentary reflectors may be less below salt overhang. Additionally, the angle of apparent dip (recall that the sections presented in this report are in time, not depth) of the reflectors may well be steeper than it would be otherwise (“velocity pull-up”).

Sandia line 12 (fig. 5) is a west-to-east profile (fig. 4) that intersects the main part of the Bruinsburg salt dome. The profile is relatively straightforward. The interpreted profile in figure 5 indicates that there is a relatively well-developed shallow salt overhang on the western side of the salt body. A less-extensive salt

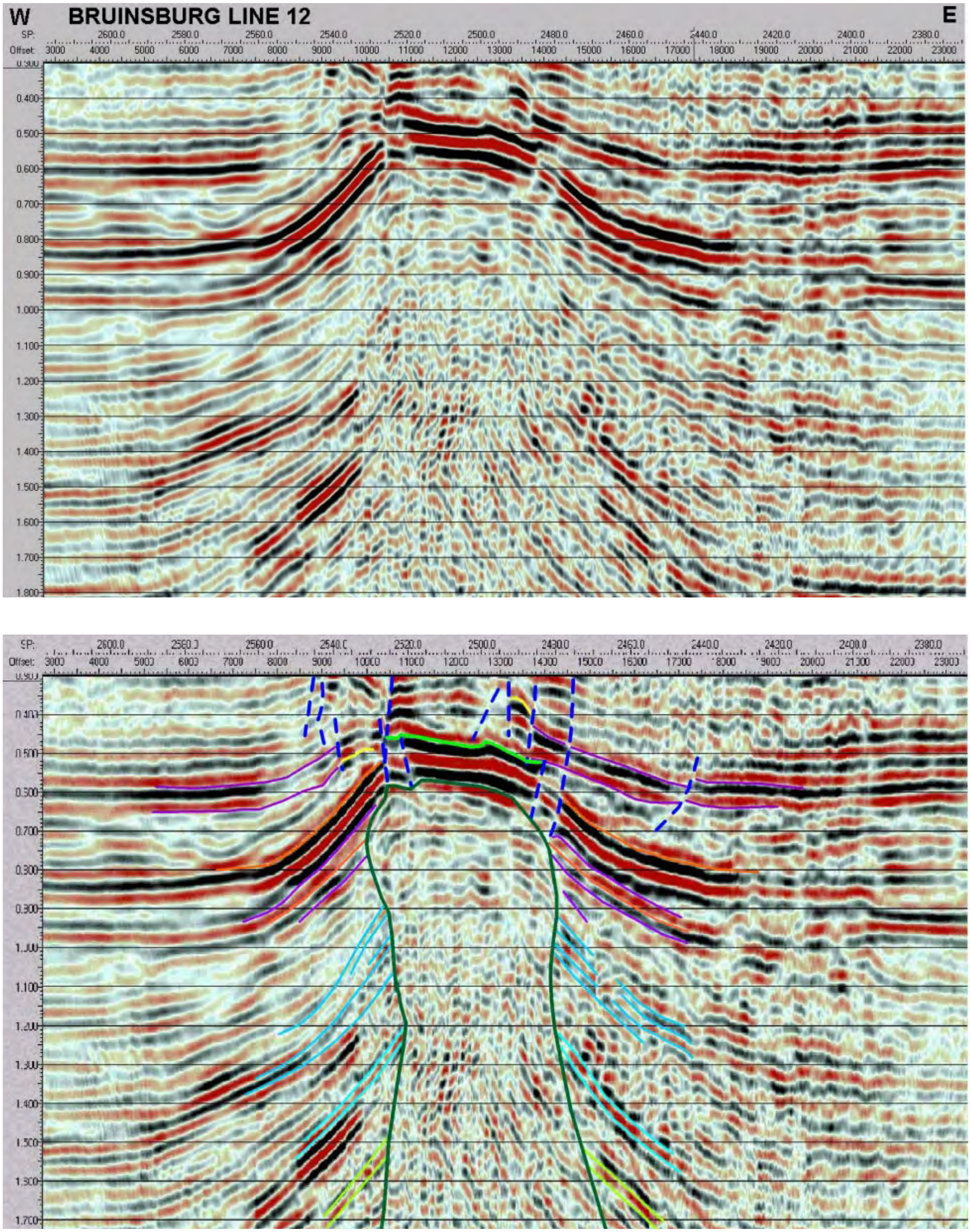


Figure 5. Uninterpreted (top) and interpreted (bottom) images of Sandia seismic line 12, showing geometry of the Bruinsburg salt dome.

overhang is also interpreted on the eastern flank of the dome.

The caprock in figure 5 is represented by the very strong, east-dipping reflectors, directly overlying the crest of the salt mass. Although these reflectors may appear to be “continuous” with a set of relatively strong reflectors off the dome, the character is somewhat different, and the division into caprock vs. sediment is believed valid. A number of faults exhibiting distinct offset have been mapped, affecting the shallow section more-or-less directly overlying the salt diapir.

The sedimentary reflectors on the west flank of the dome at about 900–1200 milliseconds (msec), two-way travel time, illustrate well the impact of shallower salt overhang. The reflectors “directly” underlying the lateral extent of the salt overhang are noticeably weaker than their downdip equivalents. The increase in apparent dip — the aforementioned velocity pull-up — is also well represented on this part of the seismic profile.

Sandia line 11 (fig. 6) is a south-to-north profile (fig. 4), intended to intersect the main outline of the dome, as it was understood prior to the survey. This profile appears much more complex structurally, than Sandia line 12. It also presents an interpretation of the salt margin that is quite anomalous, compared with most other Gulf Coast onshore salt diapirs.

The principal feature on figure 6, leading to the interpretation shown, is a block of quite strong, south-dipping reflectors, between approximately 500 and 900 msec, immediately to the left (south) of the center of the seismic image. The top-of-salt reflections are prominent to the north (right) of this block of dipping reflections. The orientation of the sedimentary and salt-related reflectors is significantly different, and there is no real continuity.

However, tracing deeper dipping reflectors, from the southern (left) edge of the profile into the mass of chaotic reflections representing the main part of the salt body, indicates that the former block of strong reflectors appears to overlie salt directly. The highlighted reflectors on figure 6, at 1100–1300 msec, provide the strongest evidence for the maximum width of the salt body at this (time) depth.

The geometric form of the boundary between salt and non-salt reflectors appears to be the curved surface of a potential listric fault. We have highlighted this curved surface on figure 6 using only the green line indicating the salt margin. A significant number of shorter, generally north-dipping antithetic faults (shown in blue) appear to segment the south-dipping block of sediments into smaller units. Additional faults have been inferred elsewhere on the profile.

The presence of an apparently down-faulted block of sediments truncating the uppermost part of a salt diapir is quite unusual. However, the existence of this geologic feature is confirmed by a third seismic profile, transecting the dome from southwest to northeast (fig. 4). This is the older Forest Oil line 2, and the uninterpreted and interpreted images for this profile are presented in figure 7.

Recall that the two Forest Oil seismic lines are of 1970s vintage. These lines also were not acquired with the intent of examining the shallow portion of the salt mass. Rather, they were acquired for hydrocarbon exploration at markedly greater depths. Sandia has reprocessed the field data, keeping in mind the former objective relevant to potential SPR expansion. The reprocessed data are what is presented in figure 7

The central part of the profile images in figure 7 is characterized by the chaotic reflections typical of the internal fabric of a salt

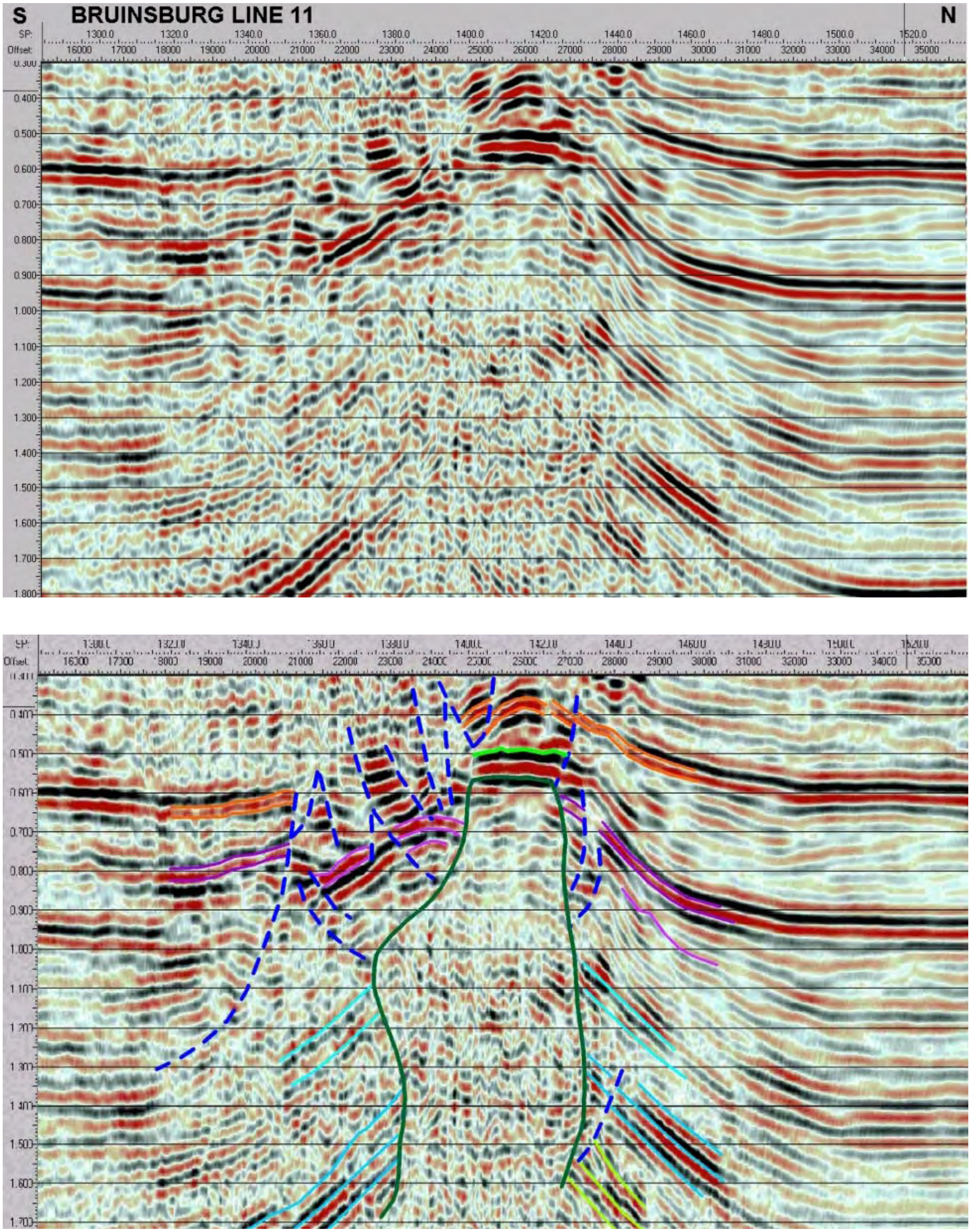


Figure 6. Uninterpreted (top) and interpreted (bottom) images of Sandia seismic line 11, showing geometry of the Bruinsburg salt dome

“Official Use Only” illustration removed

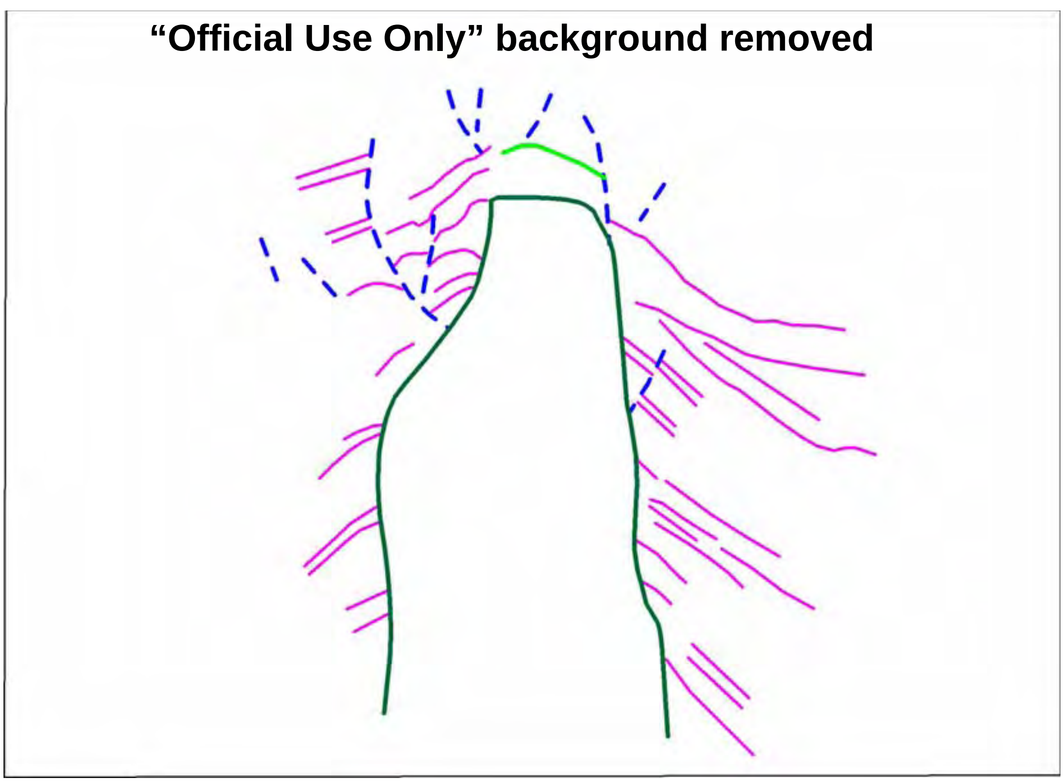


Figure 7. Uninterpreted (top) and interpreted (bottom) images of Forest Oil seismic line 2, showing geometry of the Bruinsburg salt dome. These images are for OFFICIAL USE ONLY.

mass. Flat-lying to gently dipping reflectors at the ends of the image may be traced upward to points beyond which further projection simply cannot be justified. This projection-truncation relationship is most importantly developed on the left-hand side of figure 7, between 1100 and 1600 msec. The strength of the dipping reflectors decreases markedly towards the dome. However, the overall coherence of the reflector pattern as the inward and upward continuation of unquestionable sedimentary horizons strongly supports the interpretation indicated.

As with the data presented in figure 6, the inference, from figure 7, that the southwestern part of the salt stock has been truncated along an upward-curved "listric fault" (?) surface appears inescapable. Southwest-dipping reflections overlying salt (at 500–800 msec on the left-hand side of fig. 7) are clearly present *below* the time-depth level of the top-of-salt surface, immediately to the northeast (right). Other, shorter, antithetic faults appear to dip northeastward, into this listric bounding surface.

Figure 8 presents the second Forest Oil seismic profile. As indicated on the seismic index map of figure 4, this profile is located to the east of the bulk of the other three profiles, just described. The line trends from northwest to southeast.

Examination of the uninterpreted seismic profile, shown in figure 8, together with the positions of the interpreted salt flanks on the other three seismic sections, indicates that Forest Oil line 1 appears to have missed the salt stock completely. Sedimentary reflectors are visible, inclined upward toward the center of the northeast projection of the salt stock. How-

"Official Use Only" illustration removed

Figure 8. Uninterpreted image of Forest Oil seismic line 1, showing off-dome geometry of sediments surrounding the Bruinsburg salt dome. This image is for OFFICIAL USE ONLY.

ever, it is difficult to distinguish meaningful reflections, directly below the surface trace of this 2-D line, from off-line reflections resulting from side-swipe of the dome

The fact that one may apparently trace strong, continuous reflectors up, and then immediately down the other side of this central projection, indicates that no salt is visible on this profile to a two-way travel-time "depth" of at least 1300 msec. Below this time horizon, the character of the reflections is more problematic. These depth-converted levels (circa 4500 ft) are below the depths of meaningful interest to the SPR program, and the interpretation is that shallow salt does not extend this far to the east.

Figures 9 through 12 illustrate another way of visualizing the interpreted seismic profiles, shown in figures 5 through 7. In each figure, the relevant interpreted seismic image has been mapped onto a vertical, three-dimensional plane of the appropriate orientation and size. The three profiles that depict the salt stock may then be viewed in three-dimensional perspective, using the visualization capabilities of the computer. Whereas interpreting the processed 2-D seismic profiles individually is instructive, viewing the collection of seismic images together in three dimensions provides a more intuitive, and convincing, interpretation. The individual images may be viewed as a whole and in context.

These 3-D images attempt to illustrate the consistency of the down-dropped block of sediments on the southern flank of the salt dome. In figures 9, 10, and 11, the listric-like fault (?) surface is visible on the principal profile (that most directly facing the viewer), and at least a portion of the block of faulted sediment is visible on the seismic section directly behind that foreground profile.

The unusual geometry of the salt stock, itself, is perhaps most clearly visible on the images of figures 9 and 10. The scoop-like form of the fault (?) contact between the down-dropped block of sediment and the main mass of diapiric salt is quite obvious on these and on the other sections. Note also the extent of salt overhang on the different sides of the dome.

Mapping of the Salt Margin

Plate 2, in the back of this report, presents the interpretation of the salt flanks of the Bruinsburg salt dome on each of the relevant seismic lines. Figure 13 is a smaller-scale version of this map. The "picks" of the salt flank indicated at various locations along the trace of each seismic line are color coded by depth.

Mechanistically, the selected set of depths, as indicated on plate 2 were identified and converted to two-way travel times using the time-to-depth conversion illustrated in figure 14. The curve and its underlying data are derived from geophysical logs run in the Tidelands Wilson 1-A well (table A-1). The indicated increase in sonic velocity with depth is fairly typical of onshore Gulf Coast sediments.

The positions of the interpreted salt flank along the seismic profiles of figures 5 through 7 at the two-way travel times corresponding to the desired set of depths were identified, and the identification numbers of the nearest shotpoints were recorded. To create plate 2, the various salt intercepts were simply plotted at their appropriate spatial positions along the seismic lines, according to shotpoint number. The depths corresponding to the various colored "plus" signs are indicated in the map legend.

These intercepts form the basis for structure mapping of the salt flank at each individual depth. Structure contours representing the outer margin of the salt stock were then constructed by hand, using the salt picks shown on plate 2 as the basis.The margin was mapped at 1000-ft contour intervals at a depth of 4000 ft

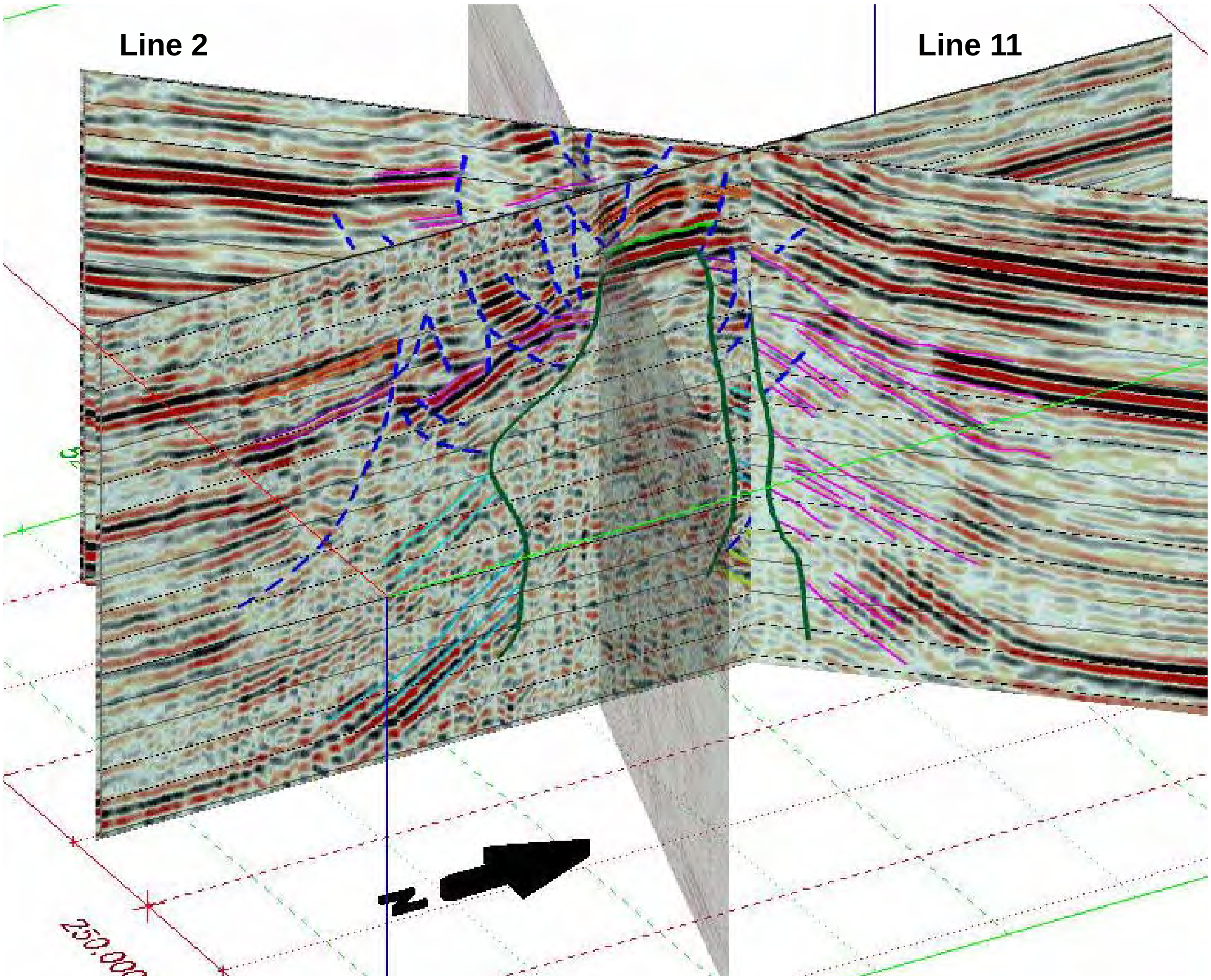


Figure 9. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 120°, elevation 30°. Sandia line 12 is partially transparent.

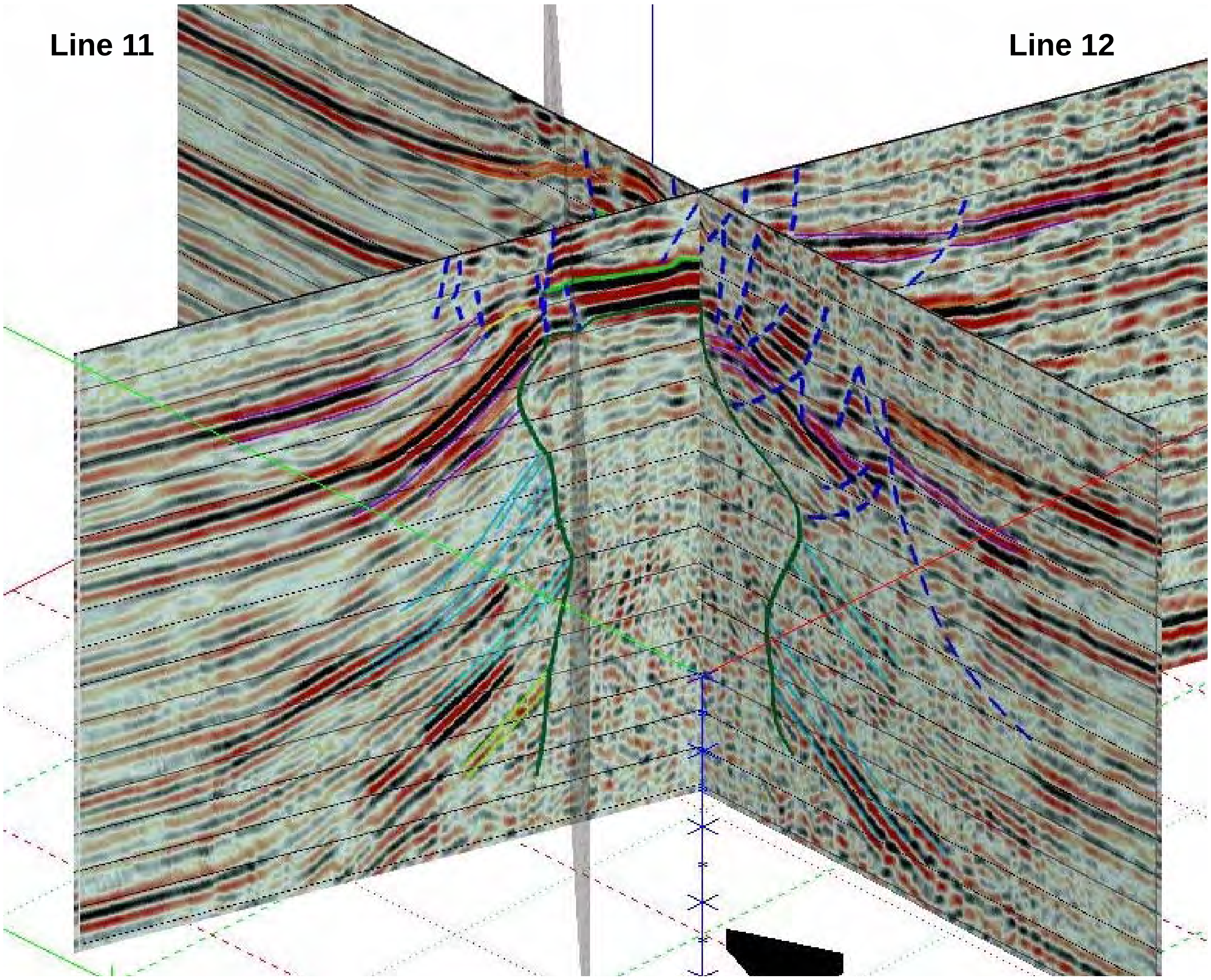


Figure 10. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 225°, elevation 30°. Forest Oil line 2 is partially transparent.

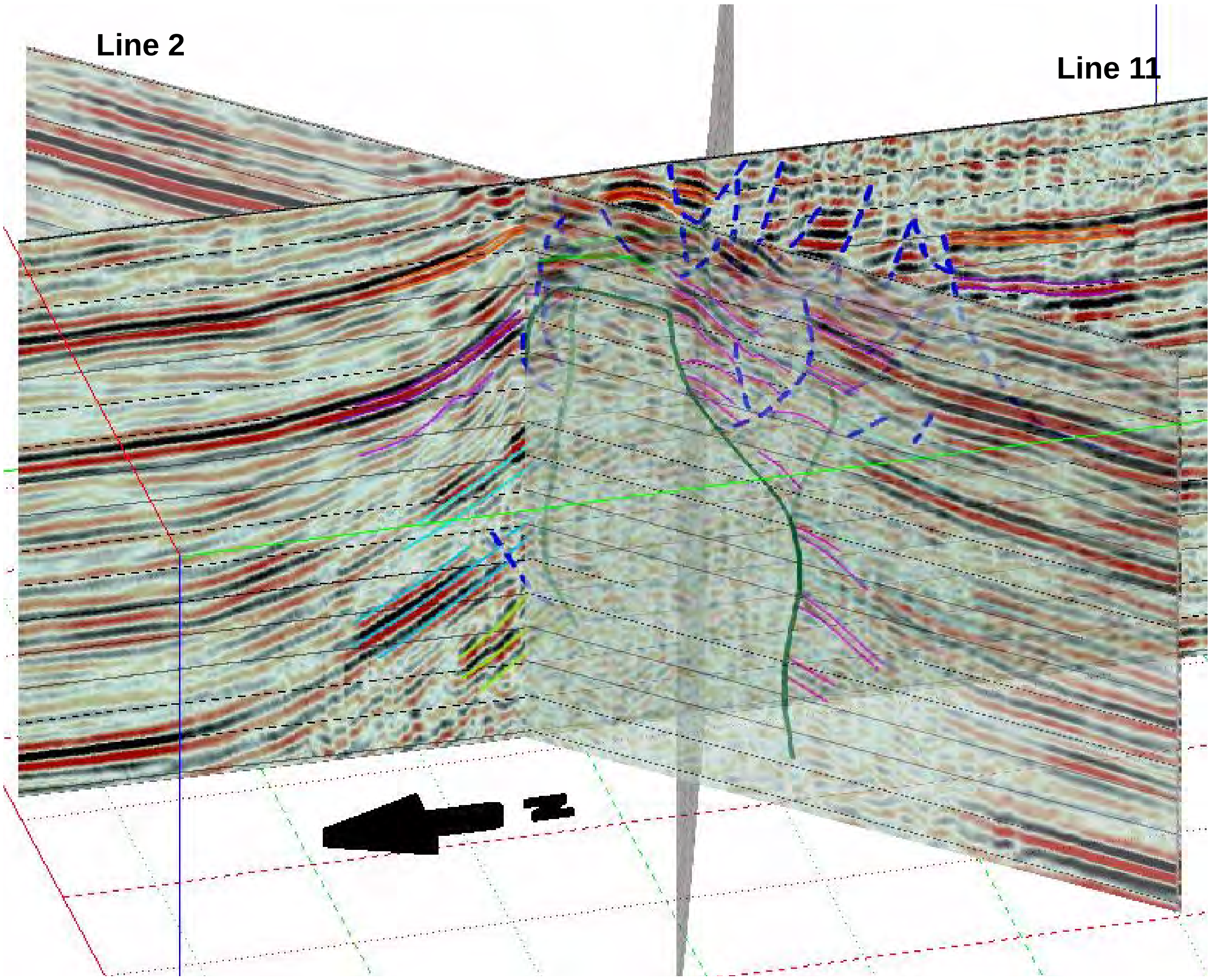


Figure 11. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 285°, elevation 30°. Sandia line 12 is partially transparent.

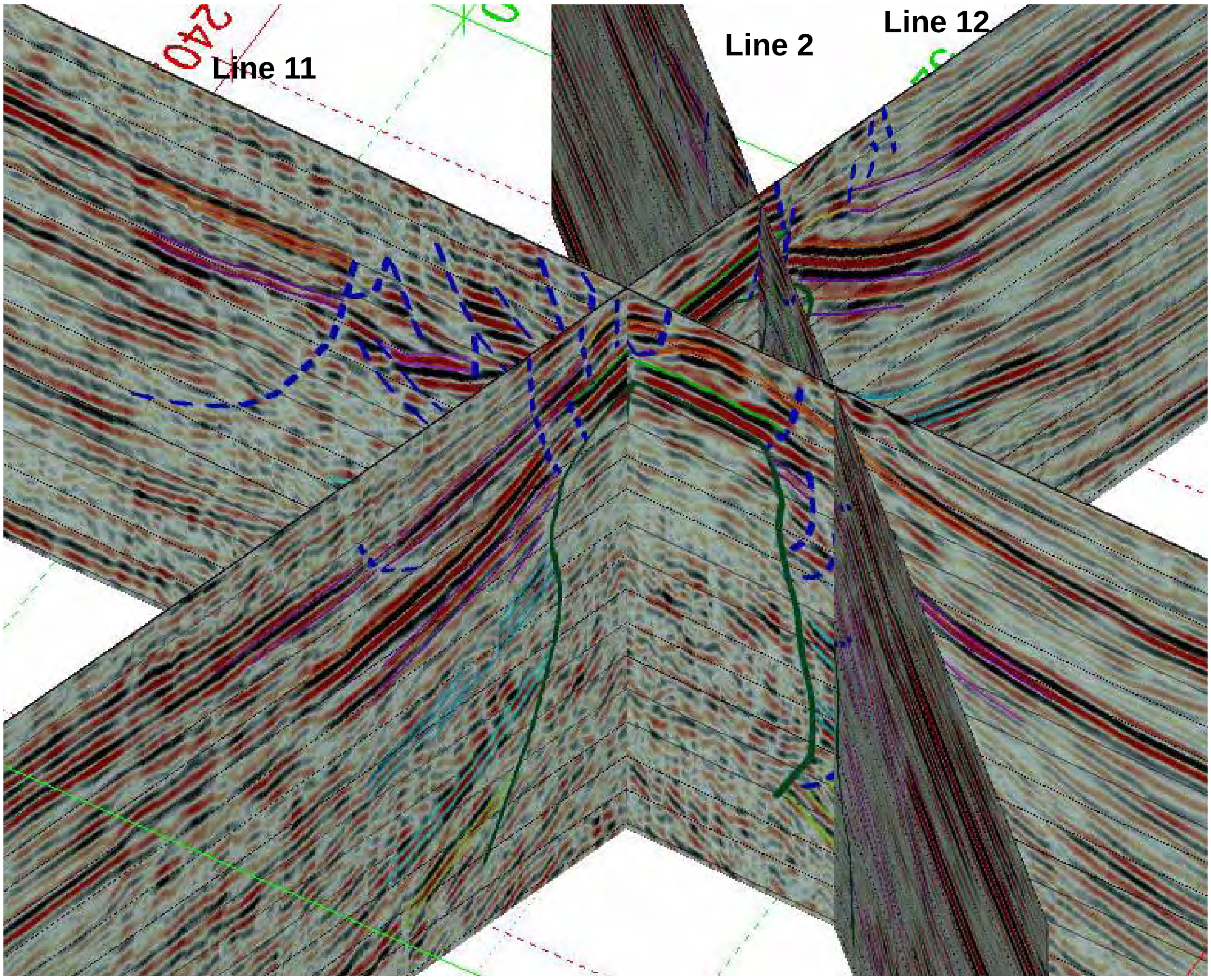


Figure 12. Three-dimensional visualization of 2-D seismic profiles intersecting the Bruinsburg salt stock. View is from azimuth 60°, elevation 50°.

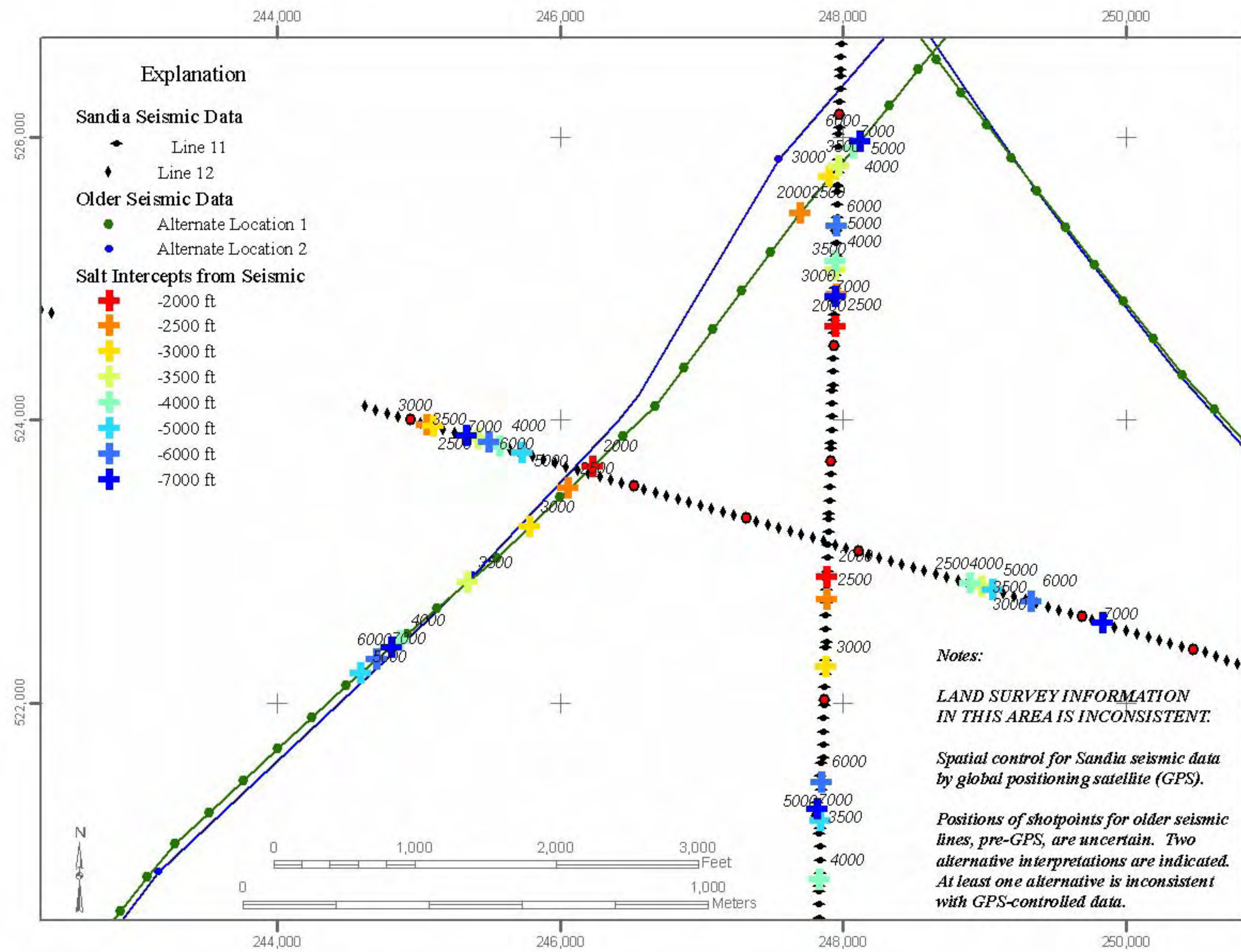


Figure 13. Small-scale map showing depth intercepts for the salt margin of the Bruinsburg salt dome on three seismic profiles. See also plate 2.

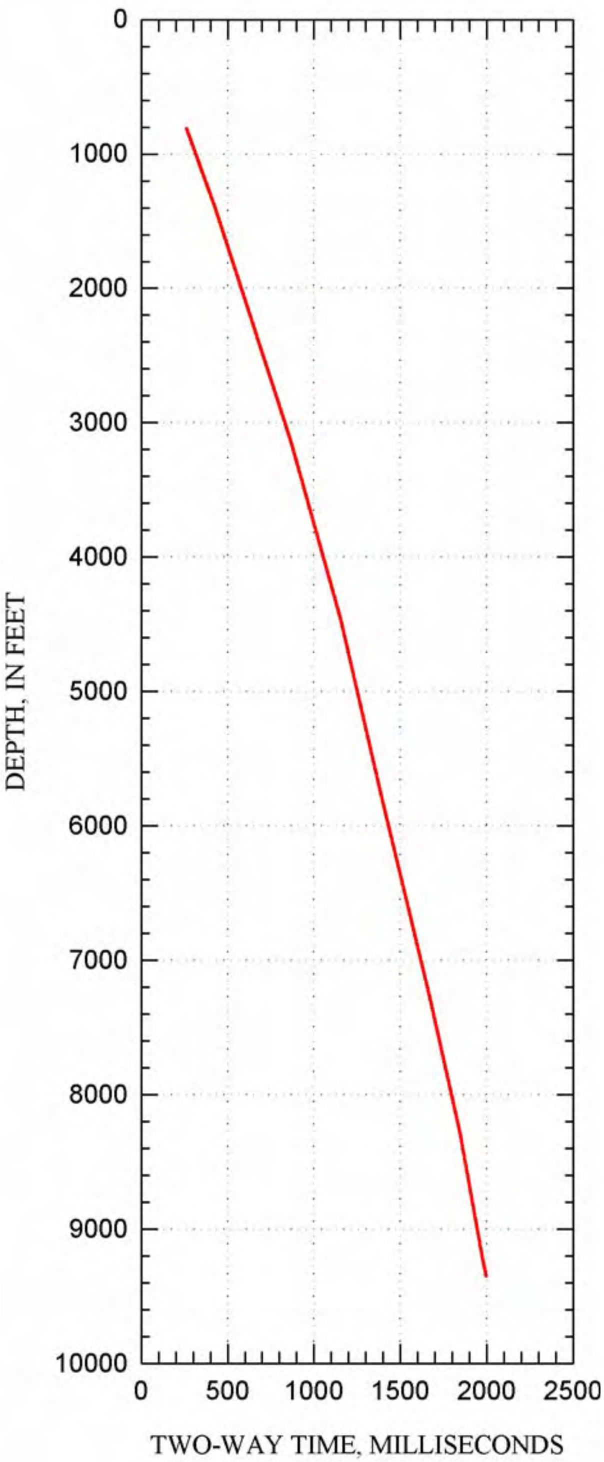


Figure 14. Time to depth conversion graph for sediments in the vicinity of the Bruinsburg salt dome. Data are from the Tidelands Wilson No. 1-A well.

and below. A 500-ft contour interval was used for shallower depths: –4000 though 2000 ft below sea level.

Mapping of the Caprock

The shallow nature of the Bruinsburg caprock poses a somewhat more difficult problem than mapping the salt. Seismic travel times are very short, making precise resolution of the depth to caprock somewhat imprecise. The small number of wells, and the need to project those caprock intercepts onto the lines of seismic profiling, also create difficulties in identifying which reflector corresponds to the actual top of caprock. The spatial uncertainty in the locations of the wells containing caprock intercepts is also a major issue, which has not been resolved with complete satisfaction.

The mapping process for the caprock is essentially the same as that described above for the salt margin. The issue of overhang appears not to be present, although it is not evident that the precision of the seismic data, particularly that of the older Forest Oil Line 2, is sufficient to reveal overhanging caprock, if it exists.

Because of the near-constant elevation of the top of caprock, we did not choose specific depth-to-time conversions and pick the contact at those travel times. Rather, we defined a number of shotpoint locations overlying the salt dome, and then we recorded the travel times to the top of caprock at those locations.

Once the time-depths to caprock were determined from seismic, these values, and the measured depths to caprock in the available set of wells, were hand contoured, making use of knowledge of the geometry of the underlying salt surface. Wells whose caprock data could not be reconciled reasonably with the salt geometry from seismic were selectively ignored, and the mismatch attributed to the spatial uncertainty issues described on page 11. Absent any evidence to the contrary, caprock was presumed to merge with the salt geometry at an elevation of –2500 ft.

Structural Interpretation

The final geometry of the caprock of the Bruinsburg salt dome is presented as plate 3. A smaller-scale image of this plate is shown as figure 15. The positions of the time-depth intercepts on the caprock surface, described immediately above, are also shown by the “plus” symbols. The arbitrary –2500-ft contour used for the “base” of caprock mapping is also indicated separately.

Important observations from the caprock structure map are the relatively low relief uppermost surface, at an elevation slightly above –1600 ft. The near-flat nature of the top of caprock over most of the salt dome is confirmed by relatively uniform measured depths of caprock intercepts in the various wells.

Also, the maps of plate 3 and figure 15 indicate a relatively major subdivision of the caprock unit, and indeed the entire salt dome, into two parts. A smaller mass of caprock is interpreted over the northwestern part of the Bruinsburg salt dome, and a larger region is present in the southeastern area. Segmentation of caprock is typically believed to indicate segmentation of the underlying salt stock into multiple, quasi-independently moving salt spines. Additional discussion of the geometry of the deeper salt, and of its influence on the interpreted geometry of the caprock, is presented below.

Plate 4 presents the final, integrated structure contour interpretation of the salt margin surface for the Bruinsburg salt dome. The same map is presented on the smaller-scale illustration of figure 16. The spatial positions of the time-depth intercepts, from plate 2, are repeated on this map to allow verification of the proper positioning of the structure contours at their known locations on the indicated 2-D vertical profiles.

There are two important implications of the structure contour map of the top of salt. First, the eastward extent of the salt stock at depth is constrained both by the locations of the salt flank on Sandia line 12 and by the absence of identifiable salt on Forest Oil line 1. This eastern limitation of the dome substantially reduces the area and volume of salt available for cavern development.

Second, the curvilinear form of the structure contours on the south side of the dome, from –2000 ft down to –3500-ft, reflect the replacement of salt by the anomalous block of southerly dipping sediments identified on the seismic profiles of figures 5 and 7. The contours have been interpreted using the expected form of a surface bounded by a listric fault. Again, the very significant restriction of the area of the prime cavern interval — from approximately 2500 ft to roughly 4500 ft — is quite evident. Below a depth of approximately 4000 ft, the salt dome is inferred to exhibit a more normal (i.e., “circular”) salt-stock margin, albeit one exhibiting as much as 800 ft of salt overhang. The greatest salt overhang is located in the southeast quadrant of the dome, below a depth of ~4000 ft.

Three-Dimensional Modeling

Once the structure contours had been interpreted, using as much geologic intuition and experience as possible, the contours were digitized and converted to a three-dimensional computer model. For the caprock, the digitized *x-y-z* values were provided as input to an interpolation algorithm within the 3-D geologic modeling software package. Interpolation is adequate in this instance, as overhang of caprock appears to be absent.

Because the interpreted seismic profiles indicate substantial salt overhang, straightfor-

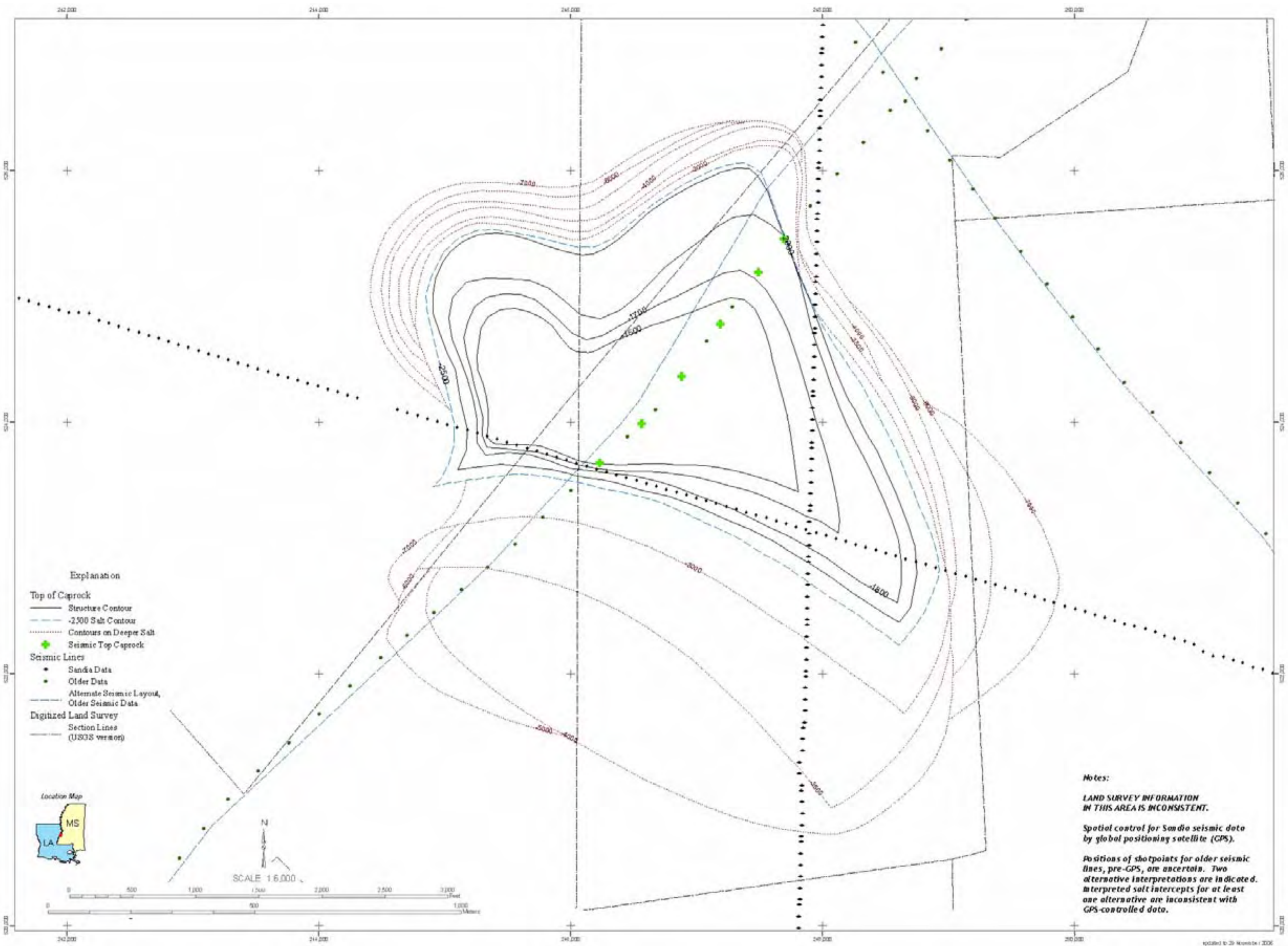


Figure 15. Small-scale structure-contour map showing the geometry of the top of the Bruinsburg caprock.

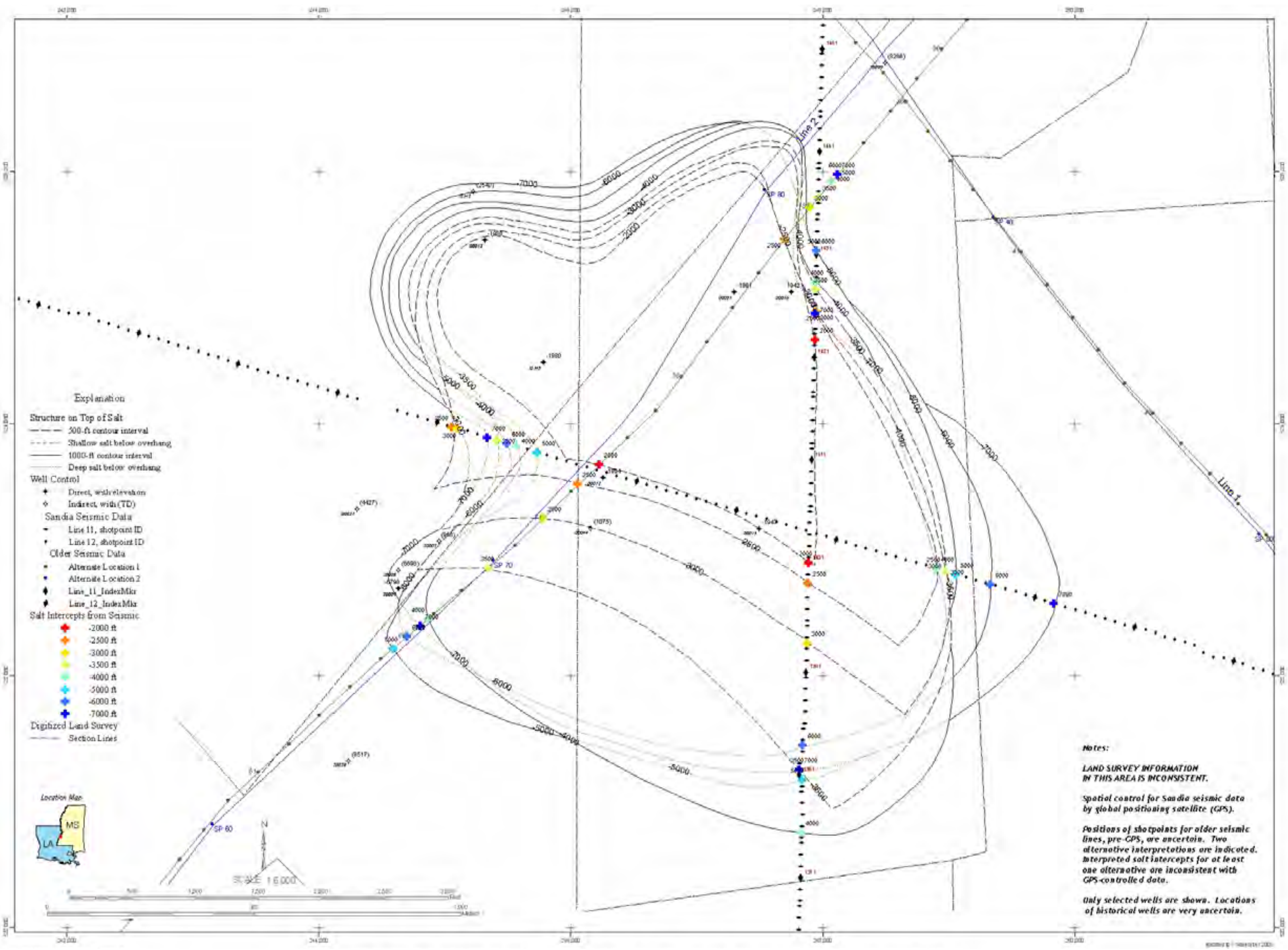


Figure 16. Small-scale structure-contour map showing the top and flanks of the Bruinsburg salt dome, as interpreted from seismic and well data.

ward interpolation of the time-depth picks is not possible for modeling the salt body. Interpolation fails completely in the presence of an overhanging surface (or recumbent folding), as the entire concept of interpolating "smoothly" between the observed intercepts makes no sense where the desired surface exhibits two elevations at the same *x*-*y* position.

The structure contours on the top of salt were modeled using the methodology of Rautman and Stein (2003). This technique involves mapping these digitized *x*-*y*-*z* values into their indicated horizontal and vertical positions in three-dimensional space, and then connecting them with a finite-element-like mesh. Proper manipulation of this mesh then allows 3-D projection and computer-based visualization.

The computer-based geologic model of the caprock is presented in top view as figure 17. This map-like visualization may be compared, more or less directly, with the actual structure map of figure 15 or plate 3. The model is colored by the subsea elevation of the surface. Figures 18 and 19 are perspective views of the three-dimensional caprock model from an elevation of 50-degrees above the horizon and at a number of azimuthal orientations. The elevation-color scheme is identical to that in the map view.

The computer model of the caprock indicates a degree of variable relief on the upper part of the caprock, although the degree of detail exhibited by the color shading perhaps exceeds the resolution of the limited data available. The smaller structural culminations

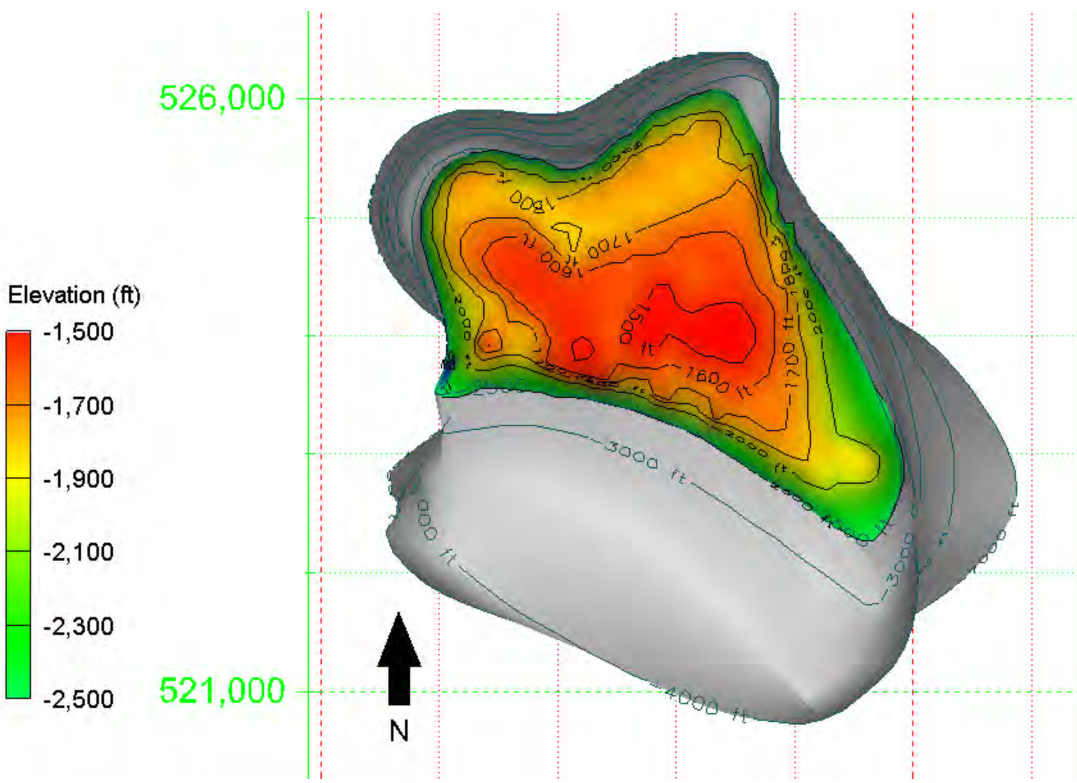


Figure 17. Map view of the three-dimensional geologic model of the caprock of the Bruinsburg salt dome. The caprock surface is colored by its subsea elevation, as indicated by the scale bar. Grey object outside the caprock region is the vertical projection of underlying salt stock. Grid squares indicate 1000-ft intervals.

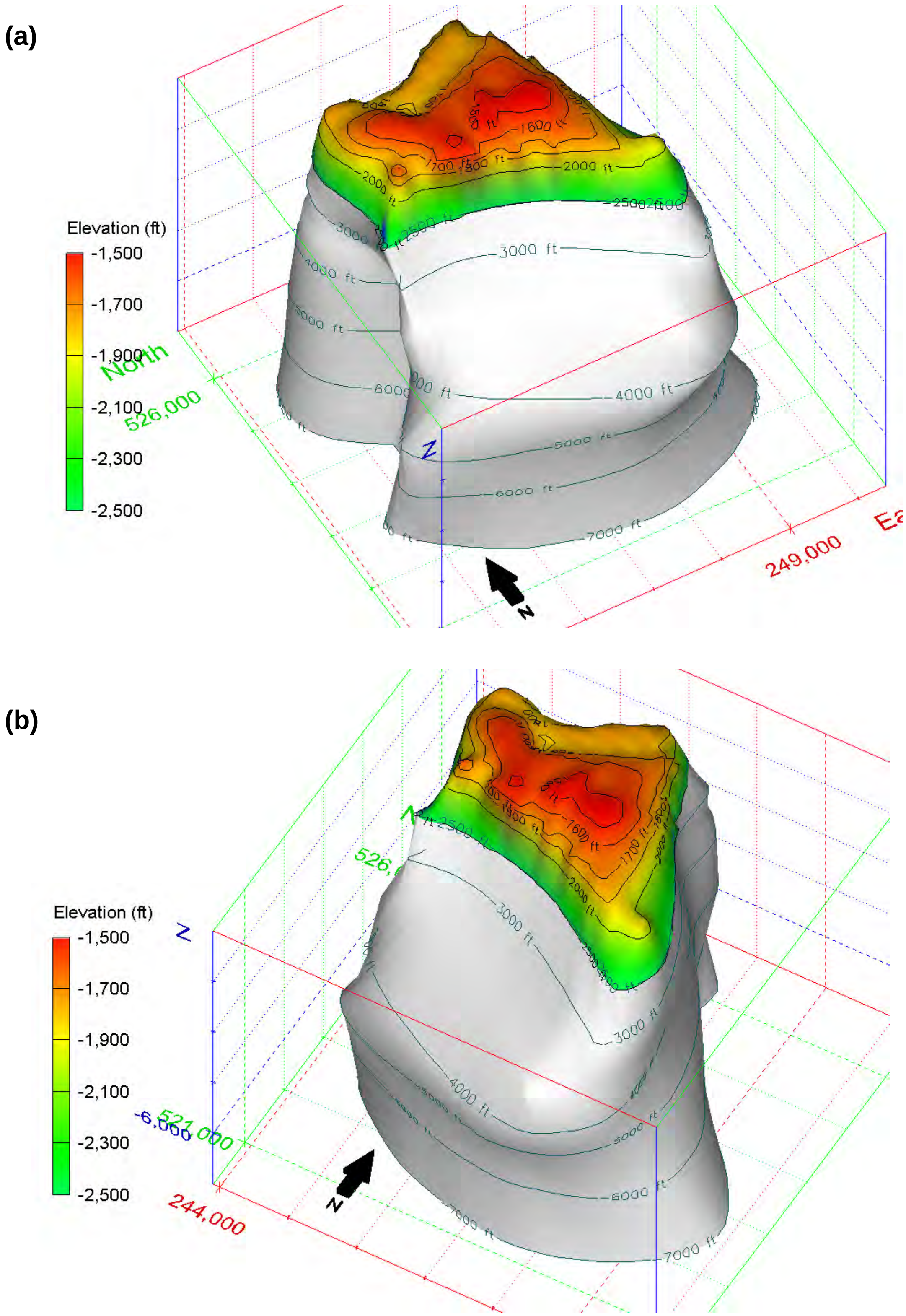


Figure 18. Perspective views of the Bruinsburg caprock model from (a) azimuth 210°, elevation 50°, and (b) azimuth 150°, elevation 50°. The caprock unit is colored by subsea elevation; grey object below the caprock is the salt flank.

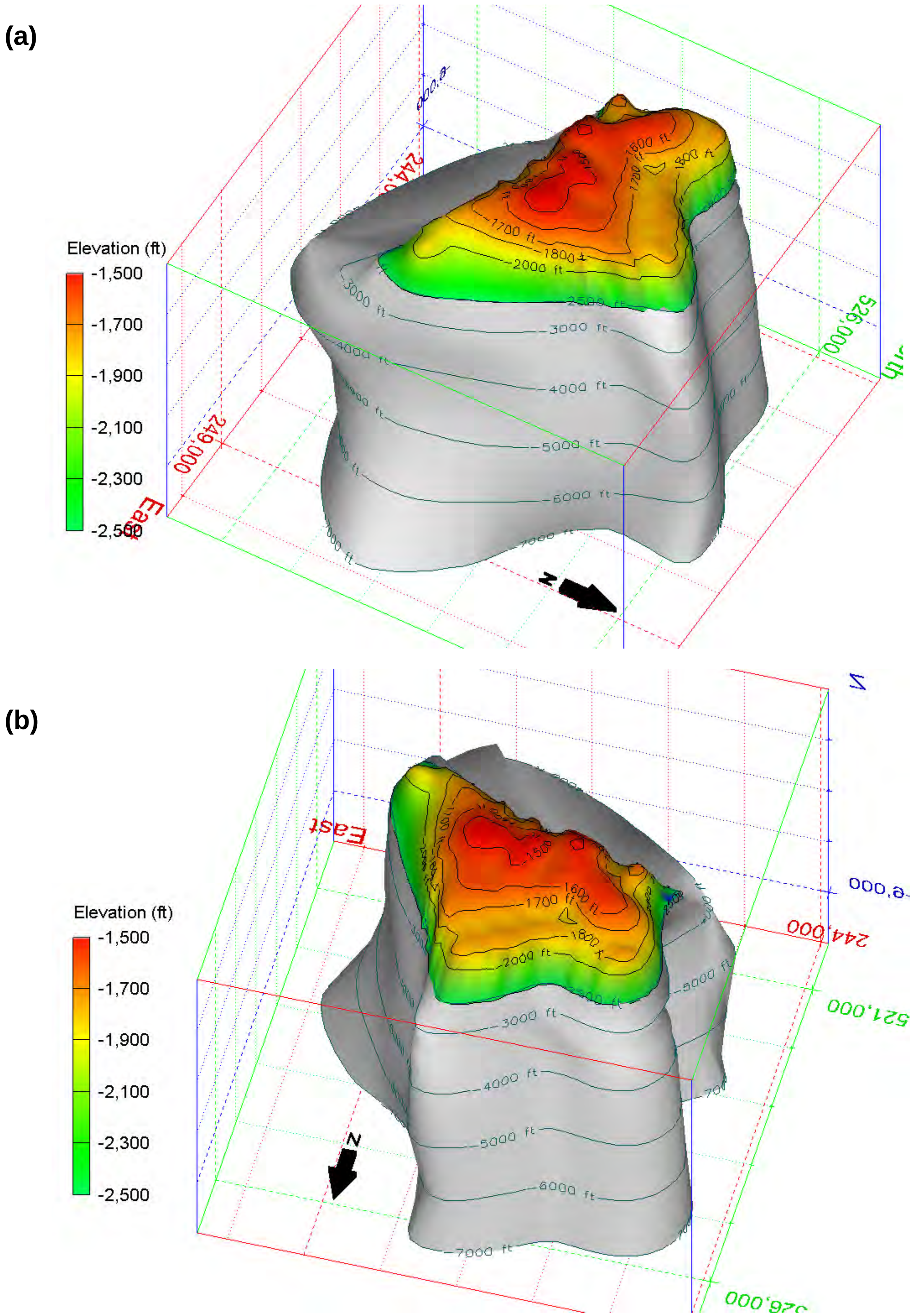


Figure 19. Perspective views of the Bruinsburg caprock model from (a) azimuth 60°, elevation 50°, and (b) azimuth 345°, elevation 50°. The caprock unit is colored by subsea elevation; grey object below the caprock is the salt flank.

are most likely an effect of the sparse data set. The arbitrary termination of caprock mapping at –2500 feet is quite prominently displayed on all model visualizations.

A map-view visualization of the three-dimensional geologic model of the Bruinsburg salt stock is presented in figure 20. Bearing in mind that this illustration is a vertical projection of a true three-dimensional object, the image of figure 20 may be compared directly to the map of plate 4 and figure 16. The dome surface is colored by its subsea elevation, as indicated by the accompanying color scale.

The irregular contour lines on the uppermost surface of the salt, shown in the most-intense shades of red, are an artifact of the numerical contouring process, within the 3-D modeling software. The upper surface of the Bruinsburg salt stock is modeled as exceptionally flat, because the uppermost surface of the salt on the seismic profiles is very difficult to resolve at a vertical spacing below that of the 500-ft contour interval selected.

The "isolines" algorithm that converts the surface mesh, representing the crest of the salt dome, to lines connecting points of equal elevation (i.e., structure contours) on that mesh

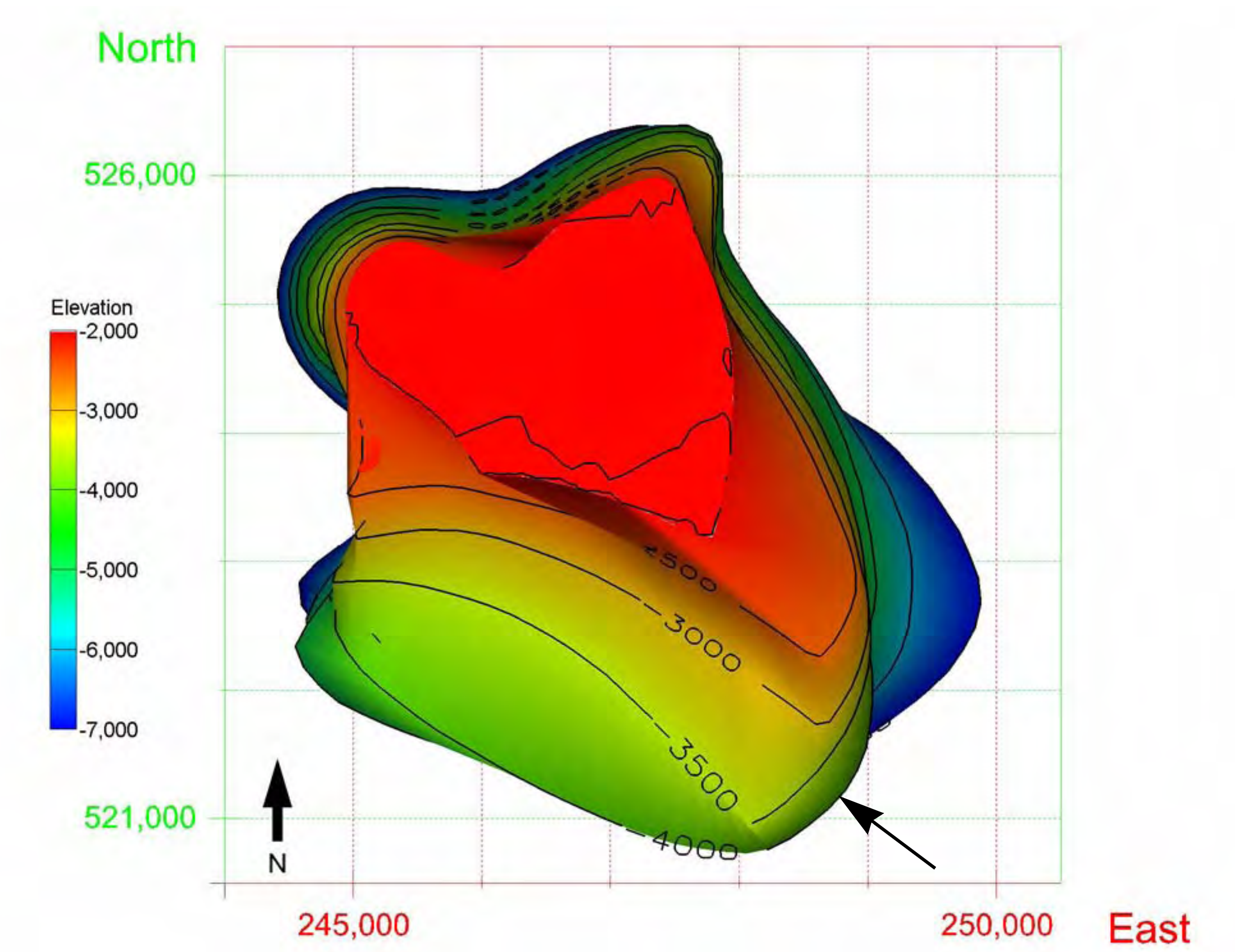


Figure 20. Map view of the 3-D model of the Bruinsburg salt dome showing the geometry of the top-of-salt surface. The principal region of significant salt overhang is indicated by the arrow. Compare to plate 4. Grid squares represent 1000-ft intervals.

becomes “confused” in the presence of many mesh nodes at virtually the same elevation. Accordingly, the algorithm may generate the “same” elevation contour (here, the –2000-ft contour) multiple times, reflecting only machine precision variations.

Figures 21 and 22 are perspective views of this same 3-D computer model, from various orientations around the compass. The geometry of the salt stock, including the very flat upper surface described above, and the irregular and overhanging nature of the steeply dipping salt flanks, are easily visualized. The elevation color scale in these illustrations is identical to that used in figure 20.

Features of note revealed by the perspective visualizations include a very marked reentrant of the salt flank on the western side of the dome. This reentrant is particularly well portrayed in figure 21(a). Another notable geometric feature is the prominent salt overhang, which affects most of the southeastern quadrant of the salt stock, below a depth of about 4000 ft. This outward bulge in the salt margin extends measures at least 800 ft, and it is quite evident on all four perspective views.

Figure 23 is another 3-D perspective view of the Bruinsburg salt stock. This view has been selected to provide an effective visualization of the listric-like fault (?) surface that forms the shallower part of the southern flank of the dome. The classical scoop-like shape of the bounding surface is clearly visible from this nearly edge-on perspective. Refer also to the 3-D visualizations of the interpreted seismic profiles, in figures 9 through 12.

ESTIMATES OF THE AREA AND VOLUME OF SALT AVAILABLE FOR DEVELOPMENT

The three-dimensional computer model of the Bruinsburg salt dome has been used to generate estimates of the area and volume of salt potentially available for the development of underground storage facilities at this site. These estimates are provided for a number of different subsections of the salt stock. The estimated areas and volumes for various portions of the entire salt mass are presented in table 1.

These estimates of the quantity of salt were computed by creating a numerical volumetric grid, with cells of known dimensions. This three-dimensional mesh was then cut by the numerical surface representing the outer surface of the salt dome (e.g., figs. 20 to 23), and the cells and portions of the cells falling outside the salt margin were discarded.

This process is illustrated in figure 24. In this perspective view, the initial volumetric mesh is shown by the light-blue regular “cubes”, occupying virtually all of the image. The 3-D model of the salt margin for the Bruinsburg dome — the cutting surface — is shown as the mostly transparent white shell (the top has been removed for clarity. The salt dome shell is contained entirely within the original volumetric mesh.

A target salt volume has been defined, and its margin is shown in figure 24 by the partially transparent cyan color. The volume is defined (arbitrarily) between –3000 ft and –4500 ft elevations. It is also restricted to the salt lying inside a 500-ft standoff zone from the actual salt flank. the top of this target volume also has been removed for clarity.

Within this target volume, a horizontal plane, shown in green on the figure, has been defined at an elevation of –4000 ft. The two-dimensional finite-element mesh blocks constituting the horizontal slice plane are shown by the black lines. To generate an estimate of the area of the “available” salt at an elevation of –4000 ft, the areas of the individual quadrilateral or triangular mesh elements are integrated.

Volumetric estimates are generated in a similar manner, only the mesh elements are

(a)

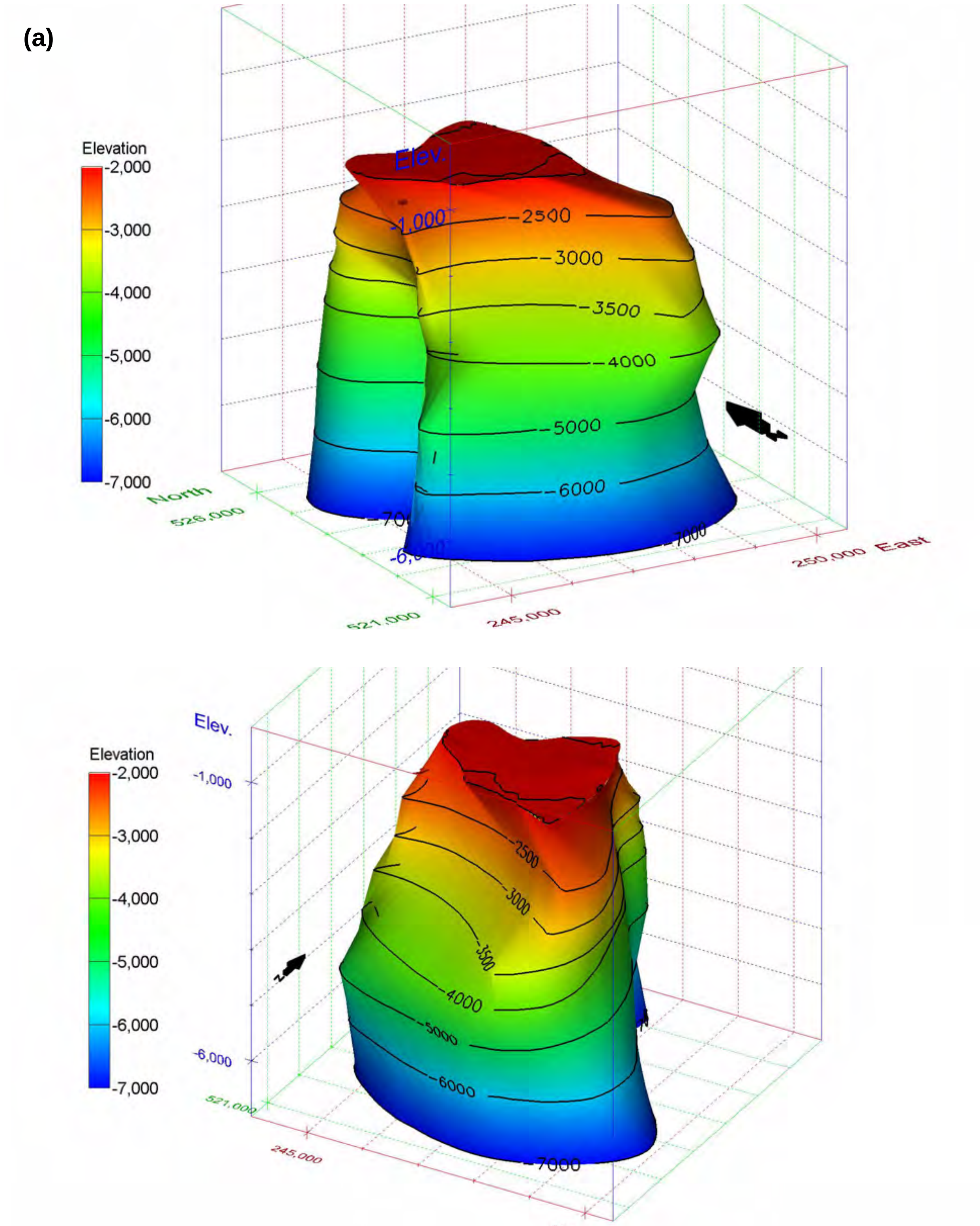


Figure 21. Perspective views of the geometry of the Bruinsburg salt dome. (a) View from azimuth 210°, inclination 20°; (b) view from azimuth 150°, inclination 30°. Color scale represents elevation, subsea. Grid squared represent 1000 ft.

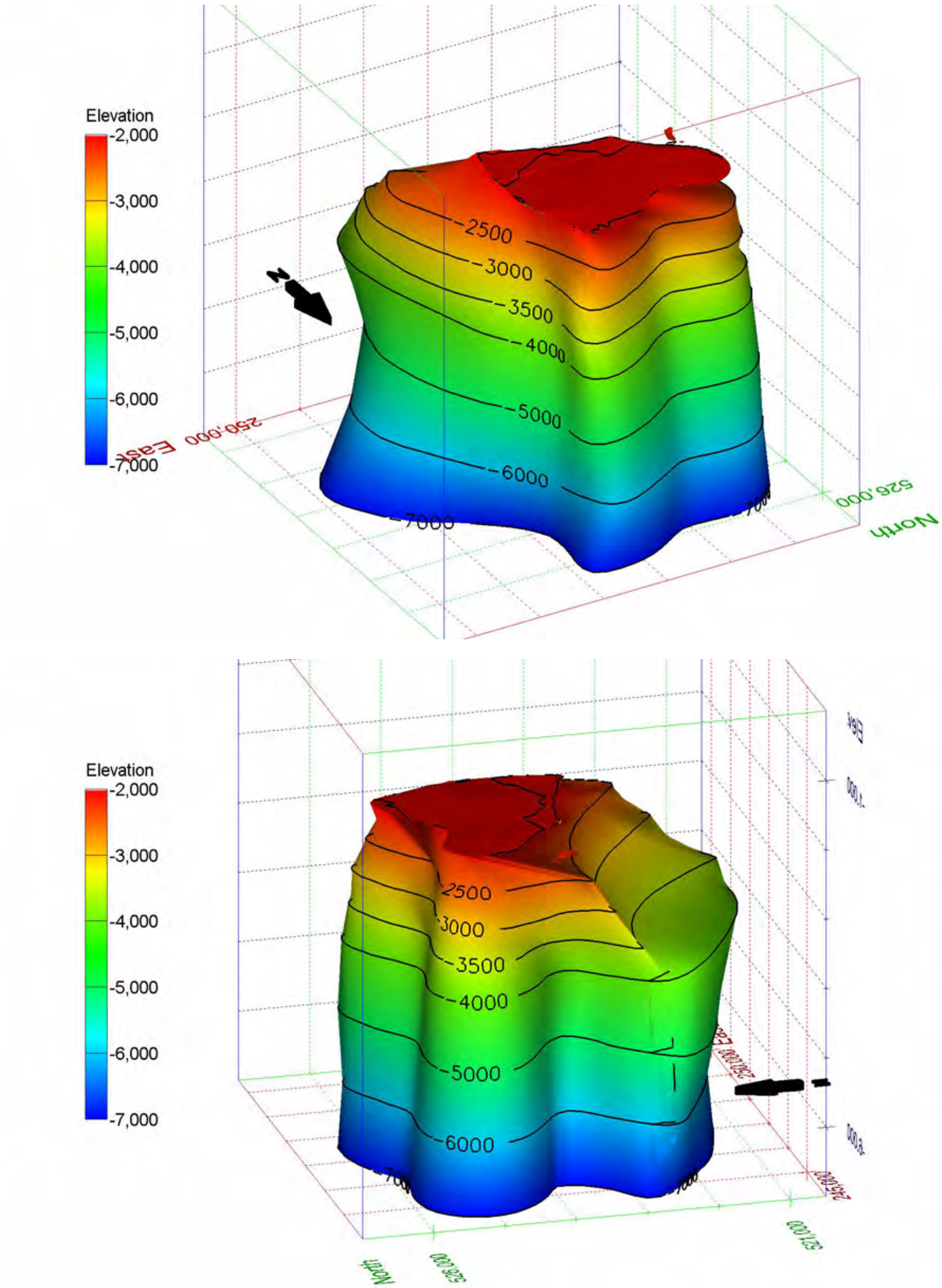


Figure 22. Perspective views of the geometry of the Bruinsburg salt dome. (a) View from azimuth 30°, inclination 30°; (b) view from azimuth 285°, inclination 20°. Color scale represents elevation, subsea. Grid squares represent 1000 ft.

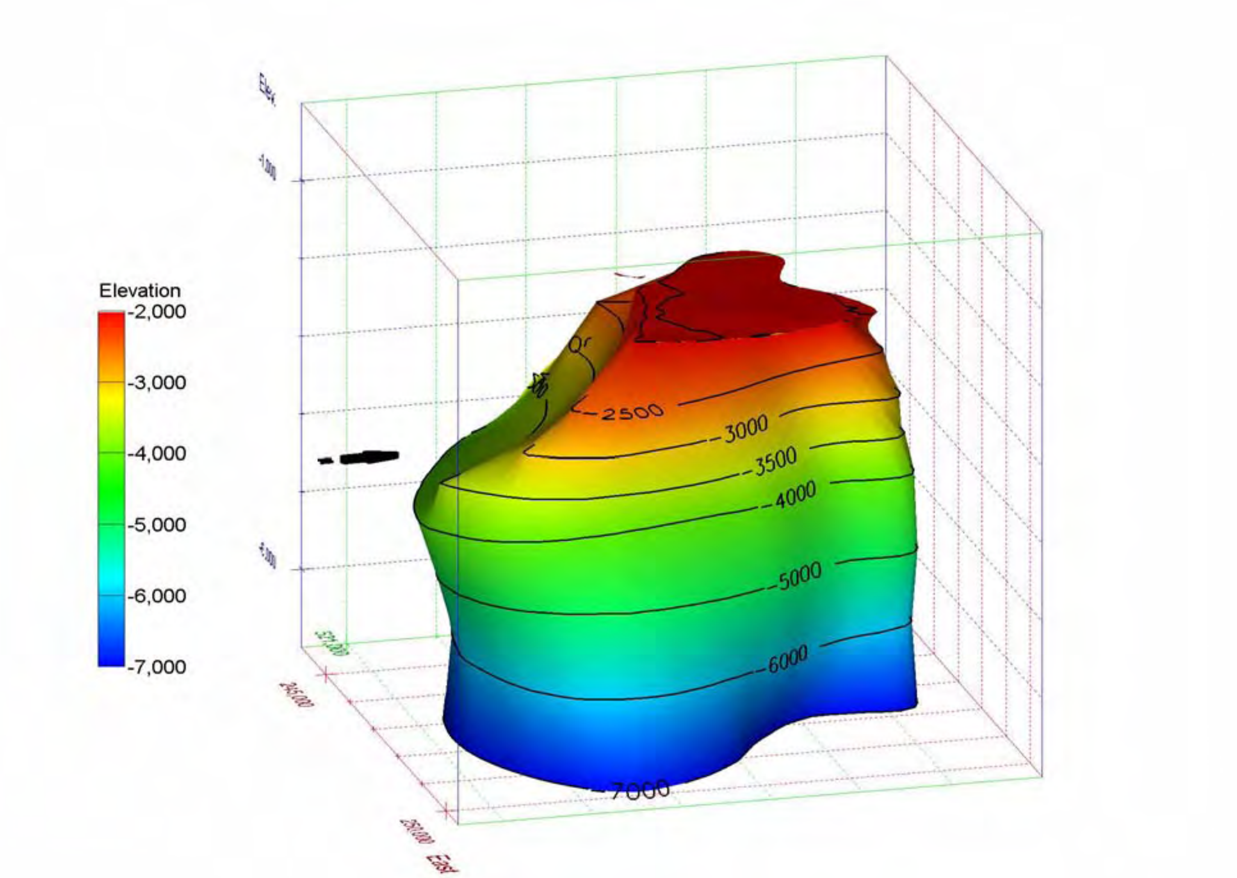


Figure 23. Perspective view of the Bruinsburg salt dome from azimuth 105°, elevation 20°, emphasizing the geometry of the southern flank, interpreted as a possible listric fault. Grid squares represent 1000 ft.

hexahedral or tetrahedral in form, and they fill the entire target volume (cyan). The volume of each three-dimensional element is computed using simple geometry, and those volumes are summed to provide the total volume. The cell-like nature of the mesh is suggested by some of the blockiness of the cyan outer volume surface in the southwestern portion of the figure. The mesh used for this conceptual example is much coarser than the actual calculational mesh used to compute the values in table 1.

The total area covered by salt at the Bruinsburg salt dome is approximately 121 acres (table 1), at an elevation of –2000 ft. this corresponds to about one-half square kilometer (0.49×10^6 m^2) of salt (0.19 sq. mile). The area of the salt stock increases markedly with depth, until the depth of about 3500–4000 ft is reached. Below this depth, the area of salt is relatively constant, below the influence of the probably listric fault. The magnitude of the increase in areal extent of the salt stock is shown graphically by the solid black curve in figure 25.

The total volume of salt present at Bruinsburg, down to an elevation of –6000 ft is roughly 54.8×10^9 ft^3, or 1.551 cubic kilometers of salt. The volume of salt within the prime cavern interval, from 2500 to 4500 ft, is 10.9×10^9 ft^3 or 0.747 km^3.

Volumetric estimates of the area and volume of salt that are present within both a 300-

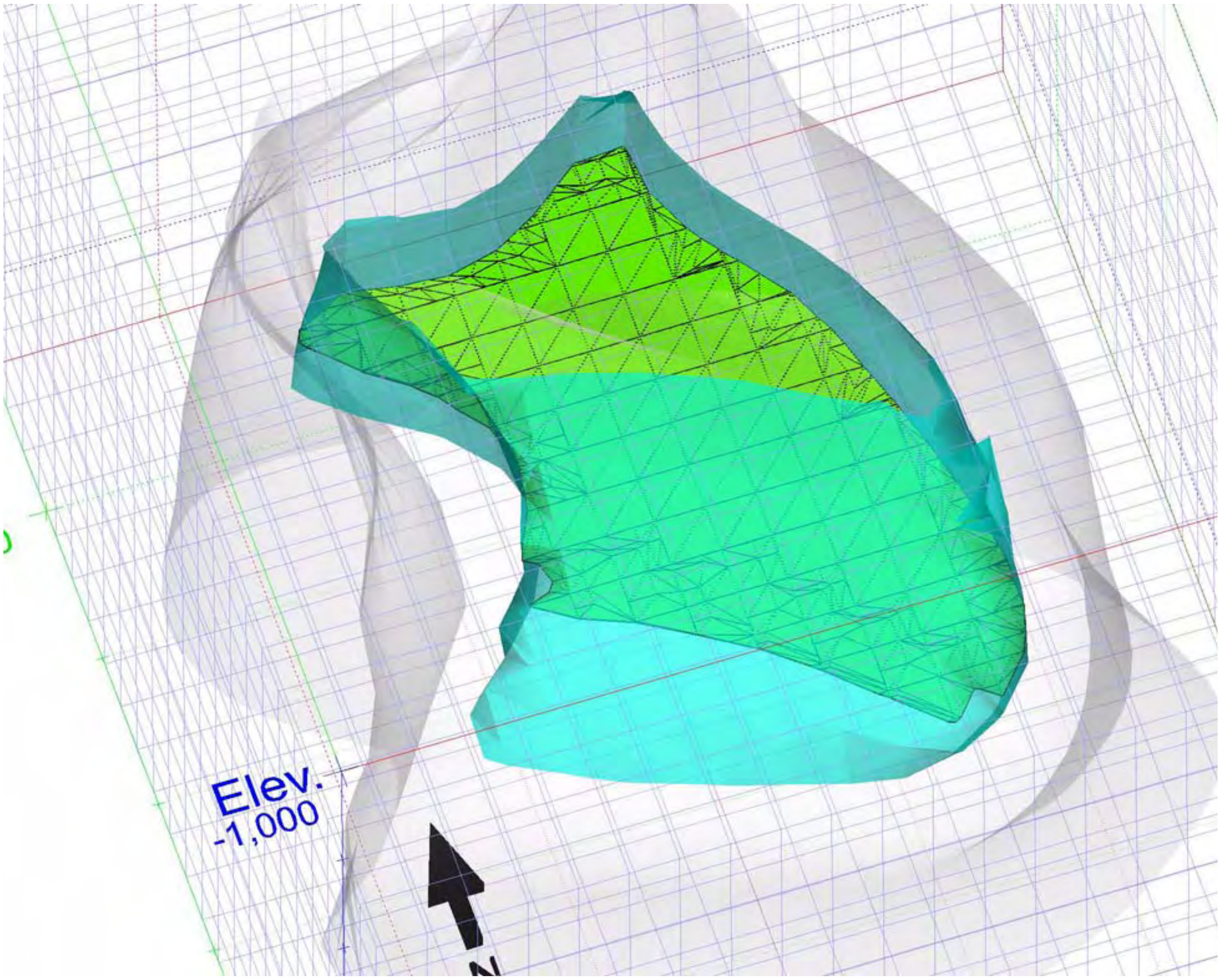


Figure 24. Conceptual illustration of generating area and volume estimates from a 3-D model of a salt dome. Salt flanks are partially transparent white; Desired volume is shown in partially transparent blue-green, and desired area is shown as green plane Black lines on horizontal plane indicate mesh cells.

Table 1: Total Estimated Area and Volume of the Bruinsburg Salt Dome
[Note use of "engineering" style exponential notation (values are even thousands)]

Area	ft^2	Acres	m^2

ft and a 500-ft standoff buffer zone of the actual salt margin have also been computed. These data are presented in table 2.

This table also presents a summary of the *decrease* in size of the Bruinsburg salt dome if a standoff distance from the modeled salt margin is enforced. Selected base (total salt) values are repeated from table 1, and both the reduced values, and the percent changes (compared to the original base values) are given. The change in area is also illustrated graphically by the dashed curves in figure 25.

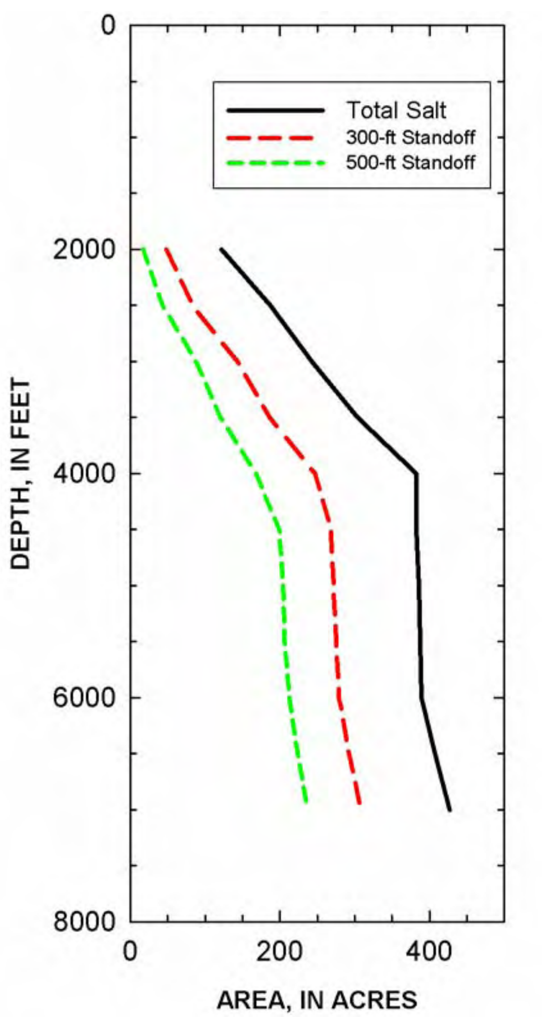


Figure 25. Increase in salt-stock area as a function of depth, reflecting apparent truncation of the upper part of the Bruinsburg salt dome

A Possible SPR Cavern Layout at the Bruinsburg Site

Sandia National Laboratories has not attempted a serious engineering design for a potential cavern field at the Bruinsburg site. However, we have produced a very simplistic sketch-layout of a number of standard, SPR Level 3 design caverns, approximately positioned on a map of the Bruinsburg salt stock. The size and spacings of these nominal caverns are approximately those required by the Level 3 design criteria.

This potential cavern layout is presented in figure 26. A larger-scale map, on which it is possible to measure actual inter-cavern distances, or on which to sketch other potential geometric arrangements of nominal caverns, is presented as plate 5, included in the pocket in the rear of this report. The maps show buffer zones of both 300 and 500 ft from the modeled salt margin

Figure 27 is a perspective 3-D view of the same information presented in figure 26. Part (a) of figure 27 presents the reduction in salt volume produced by requiring a 300-ft standoff distance from the modeled salt margin. The uncolored surface is the modeled margin, whereas the pale-blue surface is the same surface offset inward by 300 ft. Part (b) of figure 27 is identical, only the offset distance is 500 ft, rather than 300.

As indicated by figure 26, it might be possible to construct seven (7) 10-MMB standard SPR Level 3 design caverns in the depth interval 2500 ft to 4500 ft. Selection of this cavern interval essentially requires that the vertical projection of the caverns fall within the 2000-ft structure contour, in order to provide adequate roof salt above the caverns. Note that in figure 26, the sketched cavern layout does not fully respect even the 300-ft standoff distance likely to be the minimum acceptable regulatory buffer zone. An optimized cavern layout

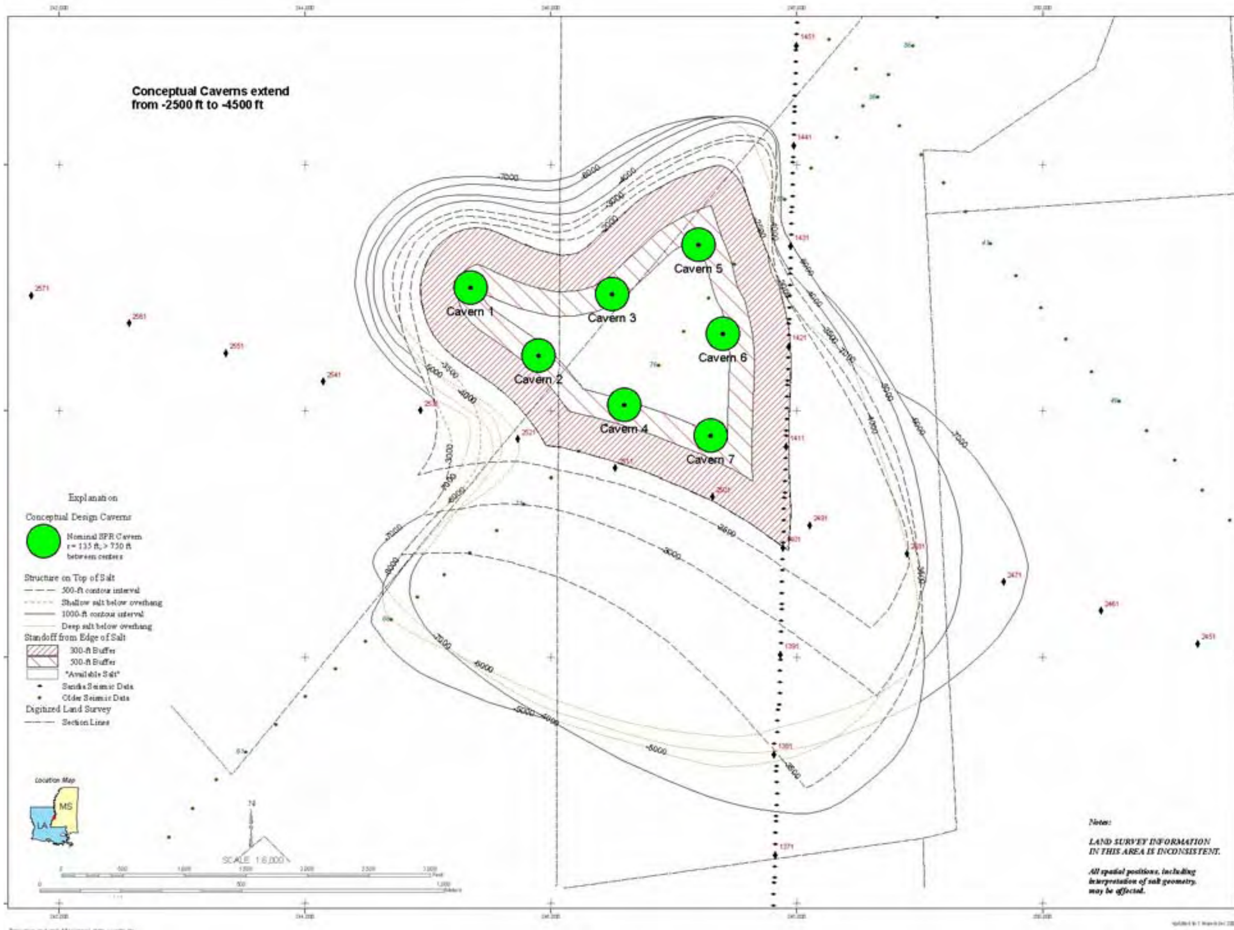


Figure 26. Schematic map of the of the Bruinsburg salt dome showing approximate dimensions of a potential SPR seven-cavern layout. Locations shown are conceptual only. Cavern diameters and spacings are approximately correct for SPR level 3 design criteria.

Table 2: Change in Estimated Size of the Bruinsburg Salt Dome Considering Standoff Zones
[Delta represents percentage change from total salt base value]

	Total Salt	300-ft Buffer Zone		500-ft Buffer Zone	
Area	**Acres**	**Acres**	**Delta**	**Acres**	**Delta**
Salt, at –2,000 ft	121	48	–60	17	–86
Salt, at –3,000 ft	242	143	–41	88	–64
Salt, at –4,000 ft	382	247	–35	168	–56
Salt, at –5,000 ft	386	272	–30	204	–47
Salt, at –6,000 ft	389	279	–28	213	–45
Volume	**km^3**	**km^3**	**Delta**	**km^3**	**Delta**
Total Salt: 0–2500 ft	0.090	0.039	–57	0.019	–79
Total Salt: 0–4500 ft	0.837	0.505	–40	0.328	–61
Total Salt: 0–6,000 ft	1.551	1.010	–35	0.707	–54
Salt: interval 2500–4500 ft	0.747	747	–38	0.309	–59

probably could be developed with additional effort. Although we do not present such a optimized map, the number of caverns that could be positioned within a 500-ft standoff zone would be on the order of only three to four. This is left to the reader as an exercise.

Discussion

Seismic data reveal an unusually complex geometry for the salt dome at the Bruinsburg site. In addition to exhibiting major deep-salt overhang, the southern flank of the salt stock is particularly unusual. As indicated on a number of the illustrations showing images of the 2-D seismic profiles, the salt body appears to have been truncated by a convex-upward listric (?) fault (?). The mechanics of how such a “fault” would have moved over time to produce the present-day geometry are unclear.

However, two of the seismic lines, Sandia line 11 and Forest Oil line 2, clearly indicate the presence of a block, or blocks, of layered sediments overlying an outward bulge in the salt flank. The relevant reflectors generally dip *away* from the salt stock — a geometry difficult to reconcile with prototypical listric displacement. However, there is some indication of dip reversal high on the sedimentary block, with apparent roll-over of dips *into* the fault (?) surface and the underlying main mass of salt. This latter phenomenon is particularly evident in the images of figures 6 and 7.

Regardless of the specific interpretation applied to the geometry of the salt flanks, it appears incontrovertible that the shallowest portion of the Bruinsburg salt dome — that within the prime interval typically used for SPR caverns — the width of the mass of salt is markedly reduced from north to south, compared with the deeper salt. The strength and overall continuity of the reflectors flanking the salt stock, and their prominent truncation at our inferred salt margin, combine to define the lateral extent of shallow salt, as we show it.

The geologic description of the Bruinsburg salt dome is significantly complicated by the major spatial uncertainty which exists in the geographic location of much of the fundamental data. This has been a major issue throughout this investigation. As indicated in figure 2, and its corresponding large-scale plate, drill hole locations appear to be completely unreliable in detail. As implied by the notation on plate 4, some of the wells, for which there are reported salt intercepts, appear to plot outside of the salt outline, at least according to one or more of the “documented” well locations. Given the evident uncertainty in these documented locations, we have felt justified in selectively ignoring (imprecise) well data that conflicts directly with the seismic interpretation. The precise locations of the two Forest Oil seismic lines are also uncertain.

Although Sandia has invested a non-trivial amount of time and effort attempting to resolve the location discrepancies in one way or another, it appears highly unlikely that the basic conclusions of this geologic investigation would be altered in any material manner. First, the general *overall position* of the Bruinsburg dome is well defined by the two new Sandia seismic lines. Positions of shotpoints on these lines were surveyed independently of the land grid. Addition of the one Forest Oil line (line 2) only strengthens the overall constraint on the dome location, even with the spatial uncertainty associated with this line (plate 2).

Second, the very small near-surface *areal footprint* of the Bruinsburg salt stock appears tightly constrained by the two Sandia seismic lines, for which the control is by Global Positioning Satellite surveying. Though one may equivocate regarding the exact nature of the geologic feature that reduces the areal extent of salt on the southern flank of the dome, the areal extent at cavern depths inescapably *is* small. The near-surface extent of the dome is

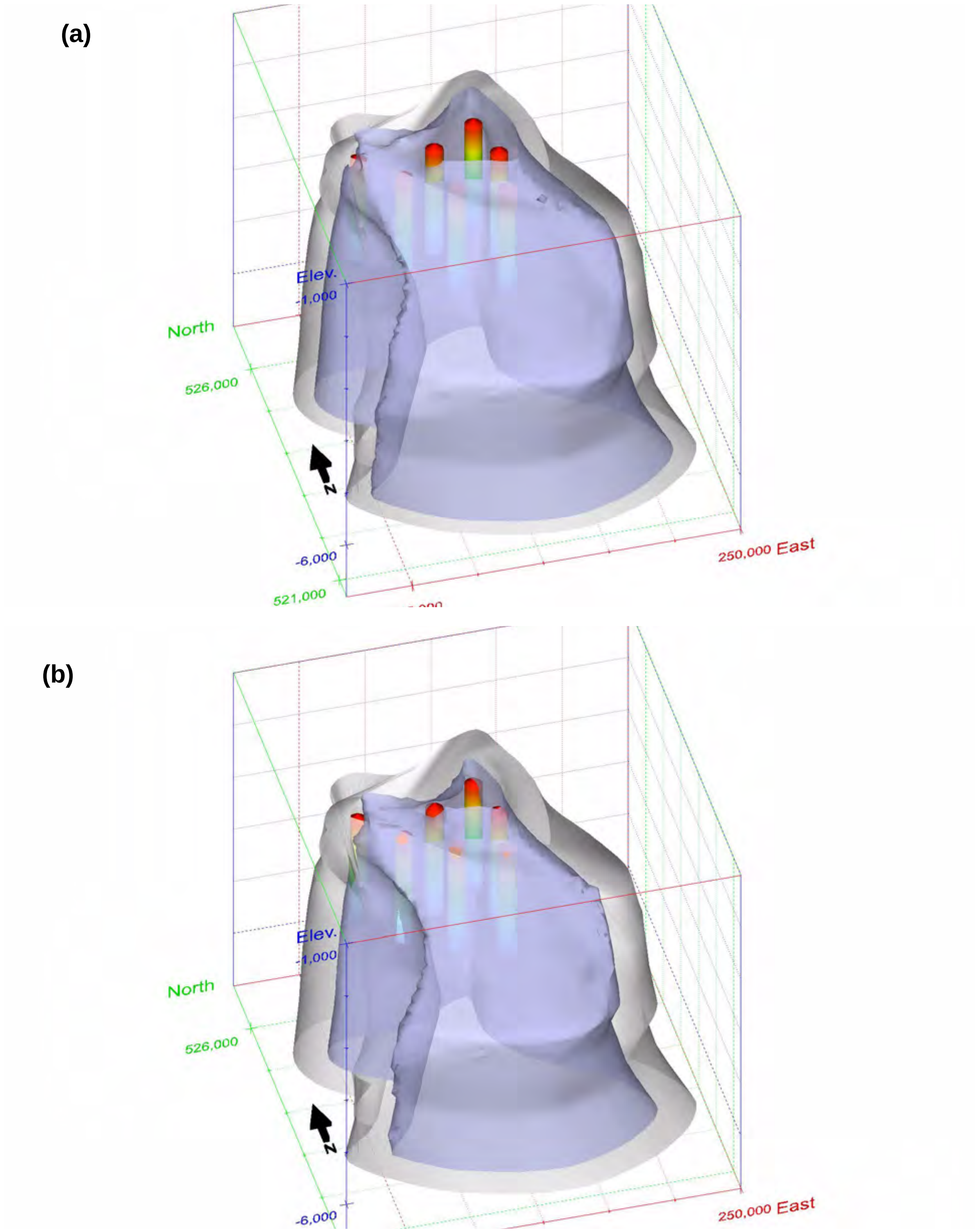


Figure 27. Perspective views of the 3-D model of the Bruinsburg salt stock showing effect of standoff buffer zones from the salt margin. (a) 300-ft standoff distance; (b) 500-ft standoff distance. Nominal cavern field from figure 26.

significantly smaller than the area of the salt stock at much greater depths.

Summary and Conclusions

The Bruinsburg salt dome is a small, shallow-piercement salt stock, less than a quarter square mile in area at the top of salt. The dome is located mostly within the flood plain of the lower Mississippi River, in extreme western Mississippi.

The geometry of the salt mass is extremely poorly constrained by well data. Only a few hydrocarbon-exploration and other wells are documented to have been drilled over the crest of this dome. Furthermore, the existing well control is both spatially biased and spatially uncertain. Reported well locations vary by 500 ft, up to as much as 2000 ft, for the same well, depending upon the source of the location information. There are at least two clusters of wells that have been drilled in close proximity to one another; this spatial clustering further reduces the effective number of well penetrations.

The geometry of the salt stock is best revealed by two generations of 2-D seismic profiling. Two 1970s-vintage seismic lines have been licensed and reprocessed. Two additional seismic lines have been acquired by Sandia National Laboratories for this study, using state-of-the-art surveying, recording, and processing technology Although one of the older seismic lines completely missed the Bruinsburg salt dome, the remaining three lines form a complementary data set that provides relatively tight control on the location and geometry of the salt.

The shape of the Bruinsburg salt dome, as revealed by seismic profiling, is quite unusual, and it is highly atypical for onshore Gulf Coast salt domes. Whereas the dome appears relatively undistinguished around the northern half of the periphery, the southern flank of the salt stock appears to have been truncated, or otherwise reshaped from the prototypical domal configuration, possibly by a major listric fault. The entire southern portion of the salt stock, down to a depth of approximately 4000 ft, has been affected. Below this depth, the flanks of the Bruinsburg dome are near vertical, although local, large overhangs of salt are identifiable.

The unusual geometry of the near-surface salt, particularly through the prime cavern interval of 2500 to 4500 ft depths, *significantly reduces* the area and volume of salt available for development of potential SPR storage caverns. Additionally, there is considerable uncertainty in the detailed form of the salt mass away from the six definitive intercepts provided by the three seismic lines. Such uncertainty, particularly on the northwestern flank of the dome, suggests that the area and volume estimates contained herein may be overly optimistic.

We conclude that it is not possible to develop an SPR cavern field consisting of 16 10-million barrel caverns, nominally of standard SPR Level-3 design, and positioned within the depth interval typically used for SPR caverns. However, it might be possible to construct a maximum of seven (7) such SPR-style storage caverns, respecting a 300-ft standoff buffer zone from the modeled edge of salt. A highly conceptual layout of seven caverns is presented in figure 26.

Note that at least two of these seven caverns are predicated upon the currently modeled shape of the northwestern quadrant of the salt stock. In fact, the extent of the salt dome in this direction is only poorly constrained. The outward extent in this part of the domal area is constrained essentially by only one direct salt intercept and one indirect control point. The well containing the direct salt intercept may be mislocated by up to 800 ft (plate1); the current interpretation is the more optimistic.

It may be possible to increase the potential storage capacity of the Bruinsburg site by constructing caverns that deviate significantly from the conventional SPR Level-3 design. Such deviations might include diameter and total height of the caverns. Such alternative designs have not been investigated.

If further investigation of the Bruinsburg site is considered, a number of field activities must be undertaken to reduce the level of uncertainty associated with this model of the salt stock. Even then, there is no guarantee that sufficient salt will be identified, at normal cavern depths, to support full SPR expansion.

First, additional seismic data, designed to image shallow (< ~8000-ft) salt, must be acquired. Several additional 2-D lines would be required. At a minimum, two to three lines should be acquired radially across the dome, in positions to "bisect' the angles formed by the three existing lines that intersect salt. Emphasis should be placed on eliminating the major uncertainty in the configuration of the northwestern quadrant of the salt mass. Additional confirmation of the geometry of the anomalous structural feature on the southern flank of the dome is needed.

Given the costs of 2-D seismic lines in today's exploration environment, it may be more cost effective to acquire a three-dimensional seismic survey over the dome area. The complexities indicated for the southern flank may be best resolved by 3-D imaging.

Second, at least one, and probably more, cored wells should be drilled into the salt stock, to maximum cavern depths, as indicated by the additional seismic data. Although there is existing salt core from the Bruinsburg dome, as described on page 10, the age of this core renders the relevance of quantitative material properties that might be measured on samples selected from the stored material somewhat ambiguous. Core should be obtained both from the "normal" (northern) part of the salt dome and from the portion affected by the anomalous structural feature on the southern flank of the dome. Logging of the core should emphasize the salt fabric (crystal size and orientation) over the entire length of the core, rather than merely providing a basis for selecting a few specimens for laboratory testing.

The final assessment is that the Bruinsburg salt dome represents a high-risk site for potential Strategic Petroleum Reserve expansion.

References

Barbour, H. 2005. *Request for consideration of additional site in Mississippi for expansion of the Strategic Petroleum Reserve*. Letter from the Governor of the State of Mississippi to the Secretary of the U.S. Department of Energy, October 27, 2005. Jackson, Miss.

DOE [U.S. Department of Energy]. 1991(a). *Report to the Congress on Candidate Sites for Expansion of the Strategic petroleum Reserve to One Billion Barrels*, Report No. DOE/FE-0221P. U.S. Department of Energy, Office of Strategic Petroleum Reserve, Wash. D.C., March 1991.

DOE. 1991(b). *Characterization for Strategic Petroleum Reserve (SPR) Expansion Candidate Sites, Vol. II,* U.S. Department of Energy, Strategic Petroleum Reserve Project Management Office, New Orleans, La. Mar. 15, 1991.

Karges, H.E., 1975. *Petroleum potential of Mississippi shallow salt domes.* Gulf Coast Assn. Geol. Societies Transactions, v. 25, p. 168–181.

Rautman, C.A., and Stein, J.S. 2003. *Three-dimensional representations of salt-dome margins at four active Strategic Petroleum Reserve sites.* Sandia Report SAND2003-3300. Sandia National Laboratories, Albuquerque, N. Mex. 70 p.

Swann, C.T., 1989. *Review of geology of Mississippi salt domes involved in nuclear research.* Gulf Coast Assn. Geol. Societies Transactions, v. 39, p. 543–551

Thieling, S.C., and Moody, J.S., 1997. *Atlas of shallow Mississippi salt domes.* Bull. 131. Miss. Dept. Env. Quality, Office of Geology, Jackson, Miss. 328 p.

This page intentionally left blank.

Appendix A. List of Oil, Gas, and Other Wells Used to Characterize the Bruinsburg Salt Dome

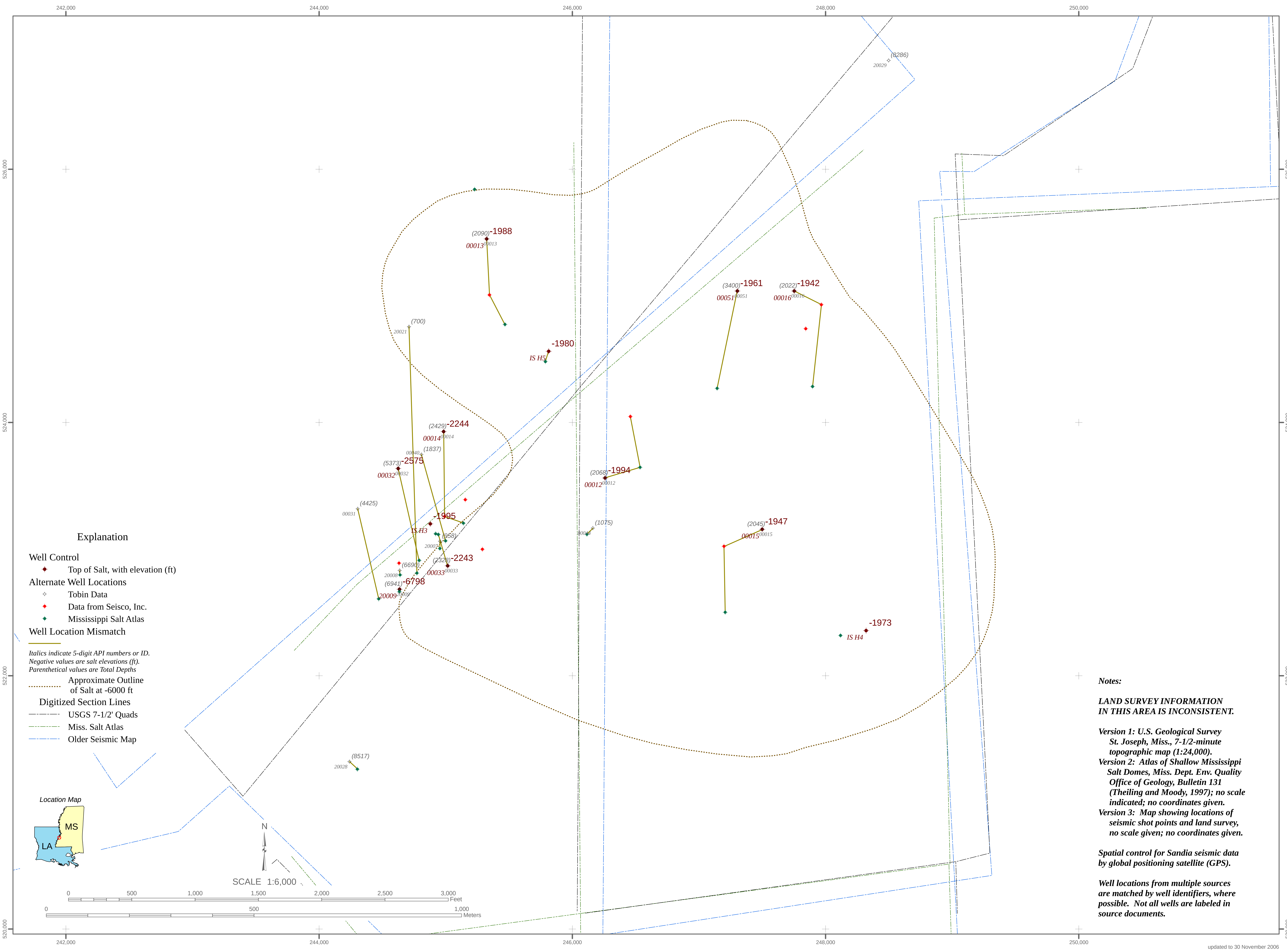
This page intentionally left blank

Table A-1: Locations and Basic Interpreted Data for Exploratory Wells Available for Characterization of the Bruinsburg Salt Dome
[Easting and northing values are Mississippi state coordinate system, western zone, NAD27, in feet, data from Tobin International, except as noted; short API numbers are prefixed by state code (23) and county code (021), and suffixed by sidetrack code (00); top of caprock (CR) and top of salt are elevations subsea; elevations and caprock thicknesses are in feet; leaders (--) unknown or not applicable. *Note that several wells have alternate locations* (sometimes multiple) documented by other sources; see plate 1 and discussion in text]

Easting	Northing	Short API	Operator	Lease	Well No.	Section	TD	Top CR	Top Salt	CR Thick
246258	523563	00012	Freeport Sulphur	Hammett W. R.	1	13	2068	1555	1994	439
245323	525450	00013	Freeport Sulfur	Hammett W.R.	2	1	2090	1978	1988	10
244983	523929	00014	Freeport Sulfur	Hammett	3	15	2430	1970	2244	274
247499	523157	00015	Freeport Sulphur	Hammett W. R.	4	13	2045	1729	1947	218
247752	525039	00016	Freeport Sulphur	Hammett W. R.	5	13	2022	1701	1942	241
269312	521665	00019	Hellenic Oil	French	1	23	10000	--	--	--
232592	508316	00020	Jett Drilling Co., Inc.	Wilson, Alex	1	15	9622	--	--	--
264097	534063	00030[1]	Rimrock Tidelands	Wilson Alex	1	20	9811	--	--	--
244305	523319	00031	Sun Oil Company	Hammett	2	2	4427	--	--	--
244624	523637	00032	Sun Oil Company	Hammett	3	1	5573	--	2575	--
245015	522870	00033	Sun Oil Company	Hammett W.R.	1A	2	2324	--	2243	0
262380	530691	00035	Justiss Mears	Wilson Alex	1	8	6504	--	--	--
523748	523748	00040	Sun Oil Company	Hammett W.R.	1	8	1837	--	--	--
246162	523167	00044	Waco Pipeline	Hammett W. R.	1	13	1075	--	--	--
247303	525039	00051	US Atomic Energy Com.	Bruinsburg Explor. Hole	1	13	3404	1697	1961	264
244955	523063	20007	Hugh Horn, et al	Hammett Farms	1	1	958	--	--	--
244636	522833	20008	Forest Oil Corp.	Hammett Farms	1	1	6690	--	--	--
244635	522684	20009	Forest Oil Corp.	Hammett Farms	2	1	6941	6625	6798	173
273350	533850	20011	Getty	International Paper	1	31	17000	--	--	--
258820	505349	20015	Shell	Compton Unit	1	45	10850	--	--	--
262100	505199	20018	Pex Pet	Compton Unit	1	45	10800	--	--	--
244710	524757	20021	Plessala, Roy A Jr.	Hammett Farms	1	1	700	--	--	--
244240	521322	20028	Southern Union Expl. Co.	Hammett Farms	1	2	8517	--	--	--
248498	526860	20029	Nuevo Energy	Hammett Farms	1	13	8286	--	--	--
245228	525841	--	International Salt Co.[2]	Hammett, W.R.	2	2	2540	--	--	--
244920	523121	--	International Salt Co.[2]	Hammett, W.R.	3	2	2733	1601	1995	394
248118	522319-	--	International Salt Co.[2]	Hammett, W.R.	4	13	2732	1728	1973	245
245787	524481	--	International Salt Co.[2]	Hammett, W.R.	5	2	2056	1846	1980	134

1 The time-to-depth conversions used in interpreting the seismic data used in this report are based upon sonic logs run in this well.
2 Information from *Atlas of Shallow Mississippi Salt Domes* (Thieling and Moody, 1997). These wells were located for mapping using the narrative location descriptions contained in the log headers.

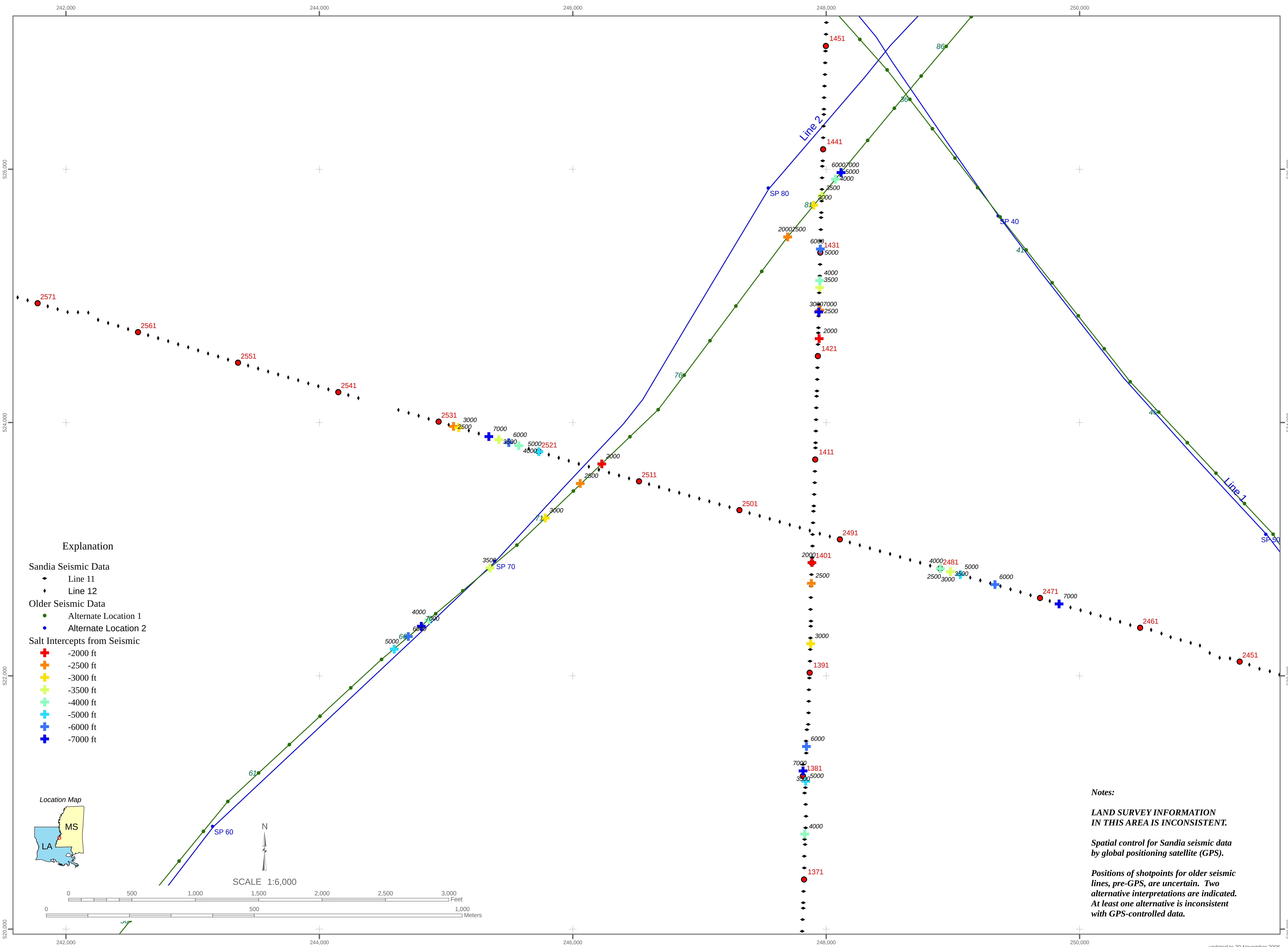
This page intentionally left blank.



updated to 30 November 2006

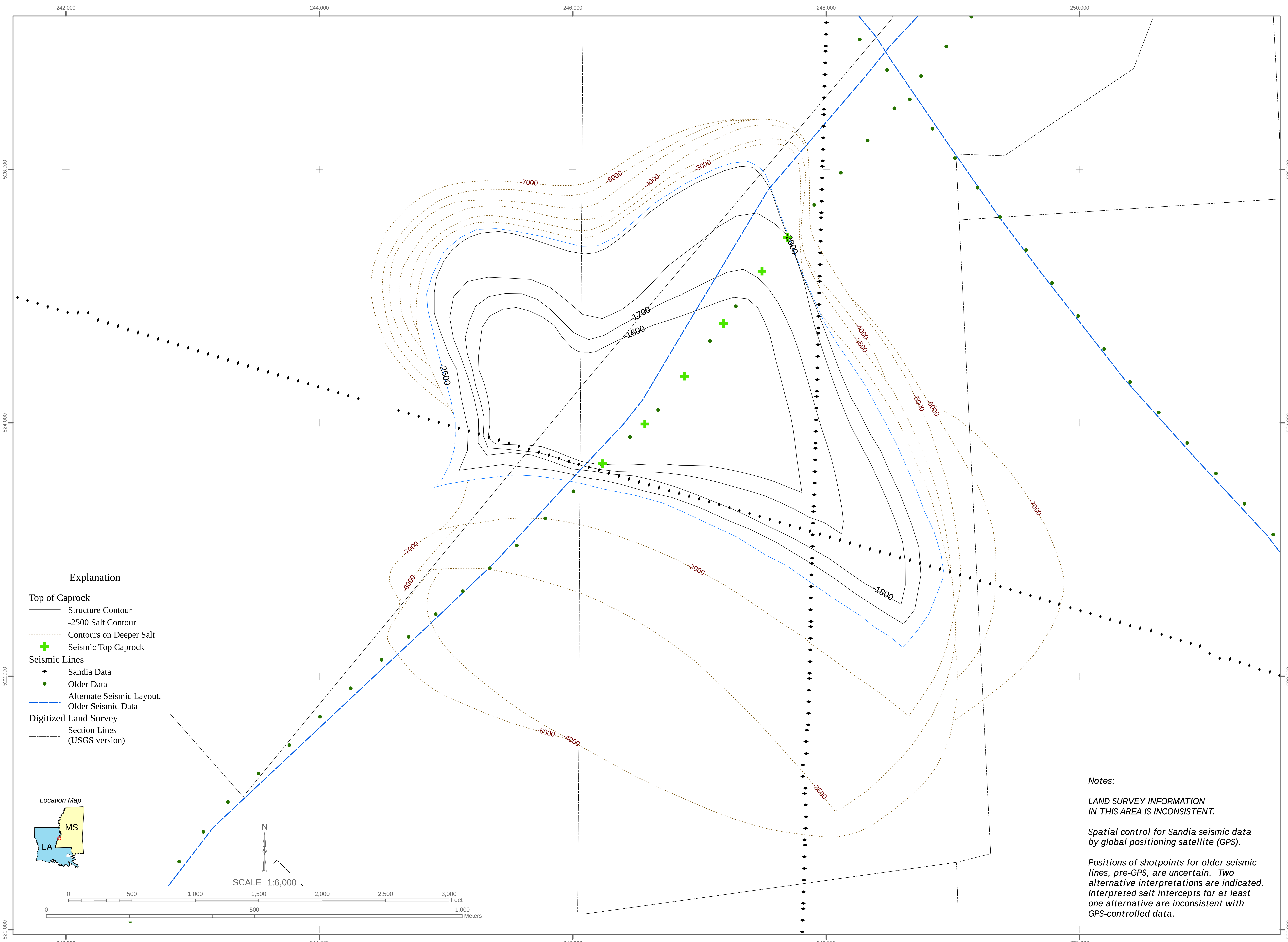
Projection and grid: Mississippi state coordinate system, west zone, in feet (transvese Mercator)
North American Datum of 1927

WELLS RELEVANT TO TOP OF SALT, BRUINSBURG SALT DOME, MISSISSIPPI



Projection and grid: Mississippi state coordinate
system, west zone, in feet (transvese Mercator)
North American Datum of 1927

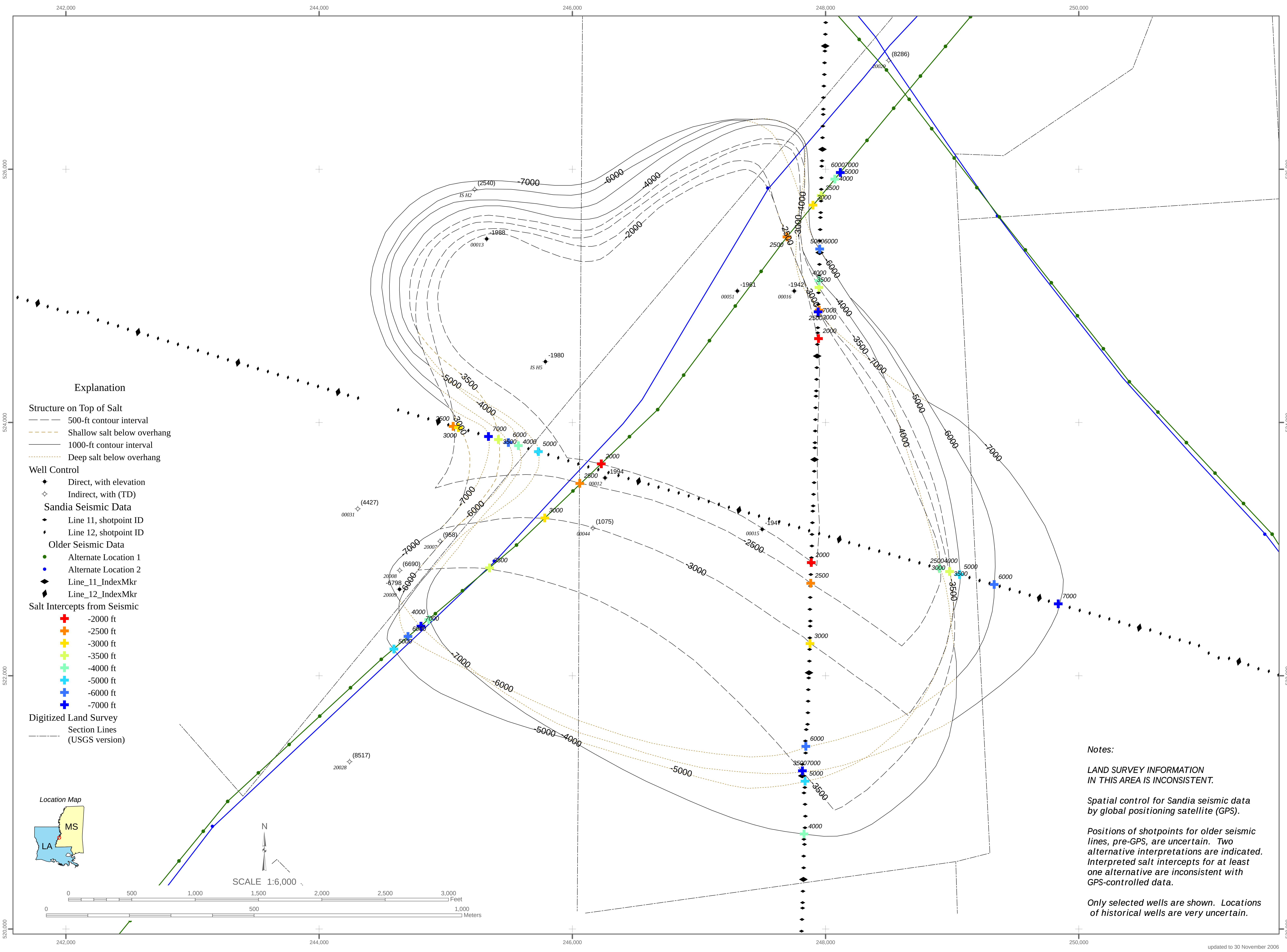
SEISMIC INTERCEPTS ON TOP AND FLANKS OF SALT, BRUINSBURG SALT DOME, MISSISSIPPI



updated to 30 November 2006

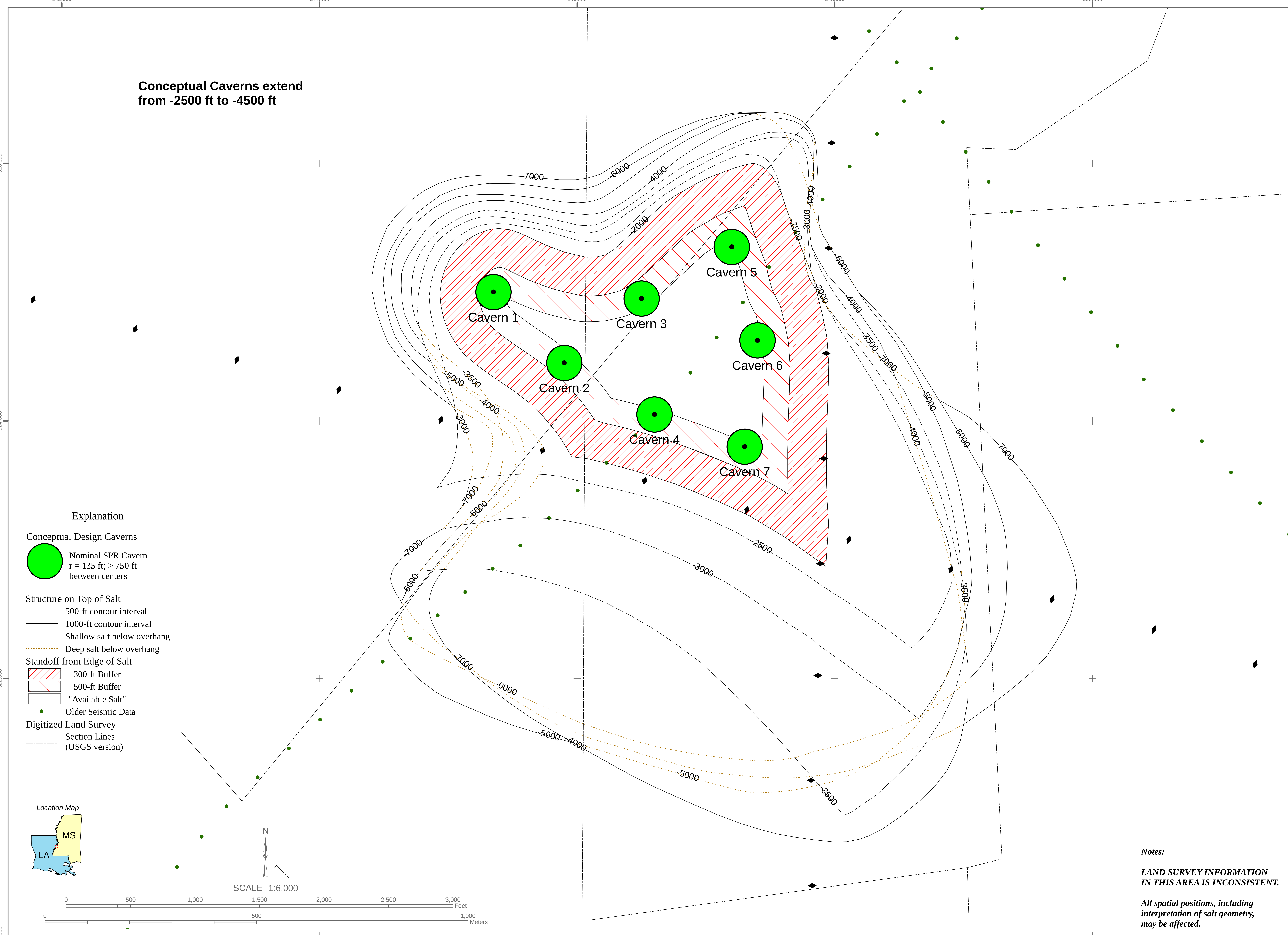
Projection and grid: Mississippi state coordinate system, west zone, in feet (transvese Mercator)
North American Datum of 1927

STRUCTURE CONTOURS ON TOP OF CAPROCK, BRUINSBURG SALT DOME, MISSISSIPPI



Projection and grid: Mississippi state coordinate system, west zone, in feet (transvese Mercator) North American Datum of 1927

STRUCTURE CONTOURS ON TOP OF SALT, BRUINSBURG SALT DOME, MISSISSIPPI



Projection and grid: Mississippi state coordinate
system, west zone, in feet (transvese Mercator)
North American Datum of 1927

updated to 30 November 2006

POTENTIAL CAVERN LAYOUT, BRUINSBURG SALT DOME, MISSISSIPPI